# CIEMAT: LMD End of Year Meeting (2025)

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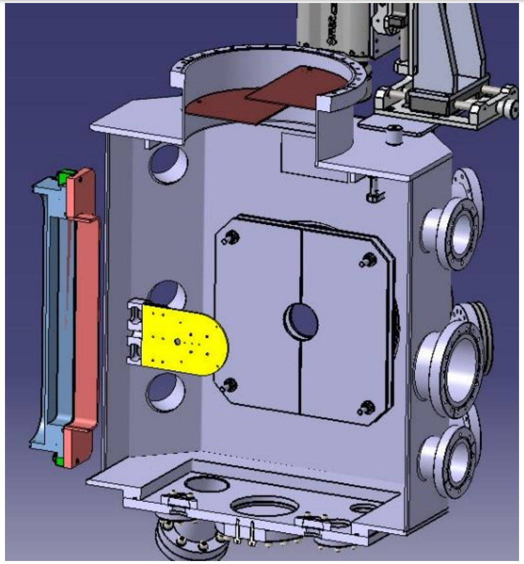
# Evaluation and plasmoid characterization of variable porosity CPS target designs under OLMAT pulsed loading (12 PM)

- Evaluate performance of **AENIUM CPS** targets using OLMAT
  - No NBI operation in 2025 due to necessary works in the generator building, in 2026 we will have NBI operation again.
  - No new CPS targets due to problems of human resources in AENIUM.
  - Targets infiltrated Sn (DIFFER) and with Li.
  - Laser loading of CPS in OLMAT at longer timescales (High frequency exposure).
- **Sn plasmoid characterization** in ELM-like and OLMAT beam pulses (A. de Castro)
- Develop conceptual design for **Li operation** in OLMAT

# OLMAT: Li upgrade

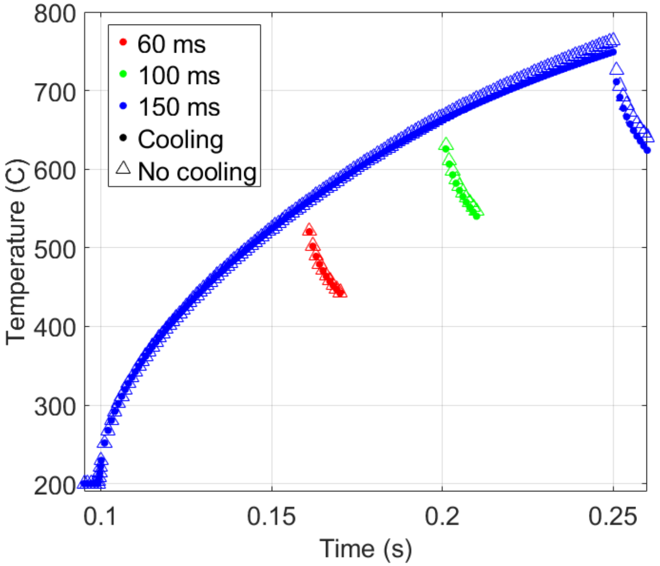
Concerns regarding **excessive evaporation** and harmful effects in NBI

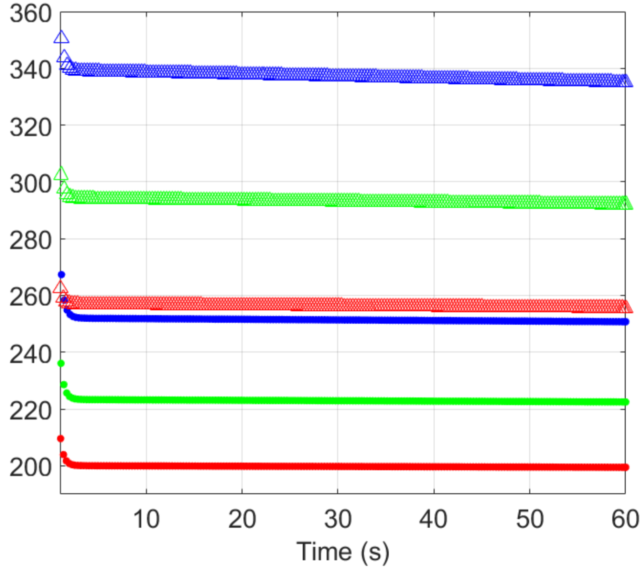
- Active cooling will **not** provide **significant effect** due to short shots (≤ 150 ms).
- **Protective shield** for the beam being designed and to be installed next year.
- Experiments with particle beam limited to 10-15 $MW/m^2$ and 100 ms to avoid overheating and contamination of adjacent valves/bellows.
- Focus on **plasma characterization** (Li local plasma, Li+-Li0 populations, vapor shielding onset and dynamics). Programmed for June 2026.



Li CPS Simulation (ANSYS):

- 10 $MW/m^2$, surface temperature during the pulse (left) and 1 s after (right).
- “Perfect” cooling model: Fixed bottom temperature.




Separate additional chamber for laser/plasma source exposure of cooled Li target

# Sn plasmoid characterization in ELM-like and OLMAT beam pulses

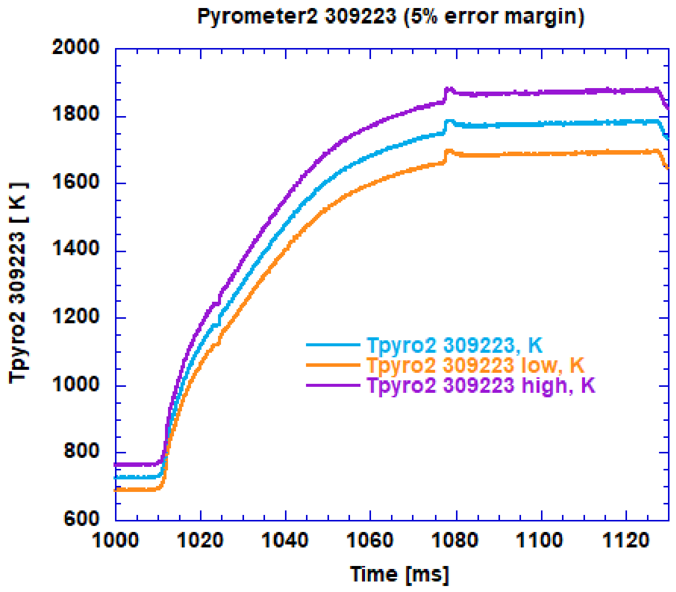
# LP measurements

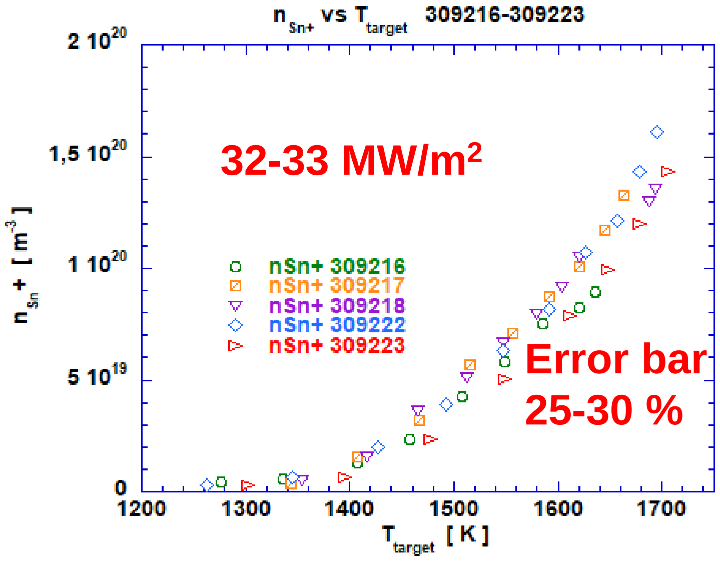
Sn wetted W felt exposure: Laser introduced at maximum power (500 MW/m$^2$) at 1076 ms. 2 shots of 33MW/m$^2$ and125 ms length + laser (309222, 309223):

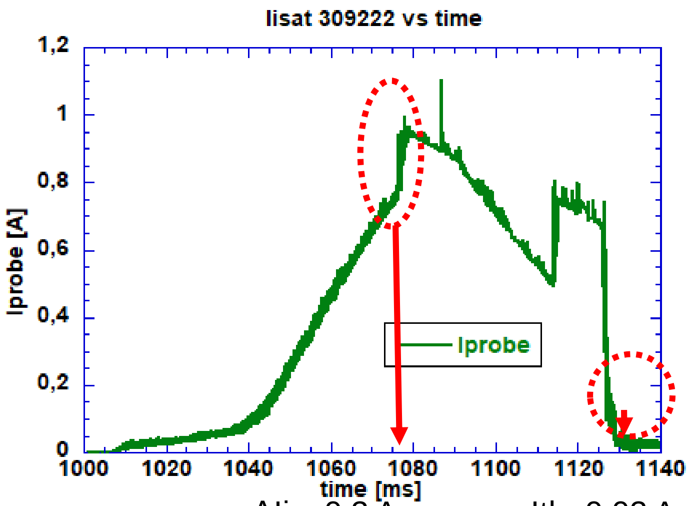
**Effect of laser transient in Ion saturation current:**

**Pronounced spike ΔIis=0,3 A but…**

- Possible effect of laser reflection on LP tip (overheating). ΔT=250 K for Ith=0,3 A
- Effect of Sn deposition on LP tip with posible increase in tip area around 10%
- Effect of particle ejection in Iprobe detected in laser trials (increase in electron current but not in ion one)→Increase in ion saturation is produced due to **interaction between ejected Sn particles and plasma.**
- DAQ ampliflier saturating at LOP110 =5 V (Iisat= 1 A). Introduces weird signal evolution with oscillations
- Future experiment: scan laser power with upgraded probe system (avoid signal saturation)
- **Target reaches an stationary temperature regime around 1750-1800 K**




ΔIis=0,3 A TLp=2700 K

Ith=0,03 A TLp=2450 K

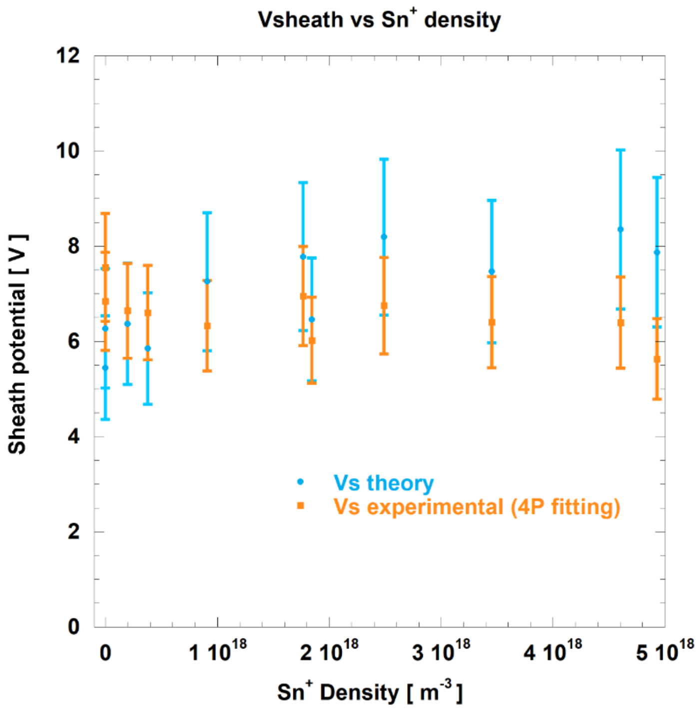
# Plasma Sheath analysis

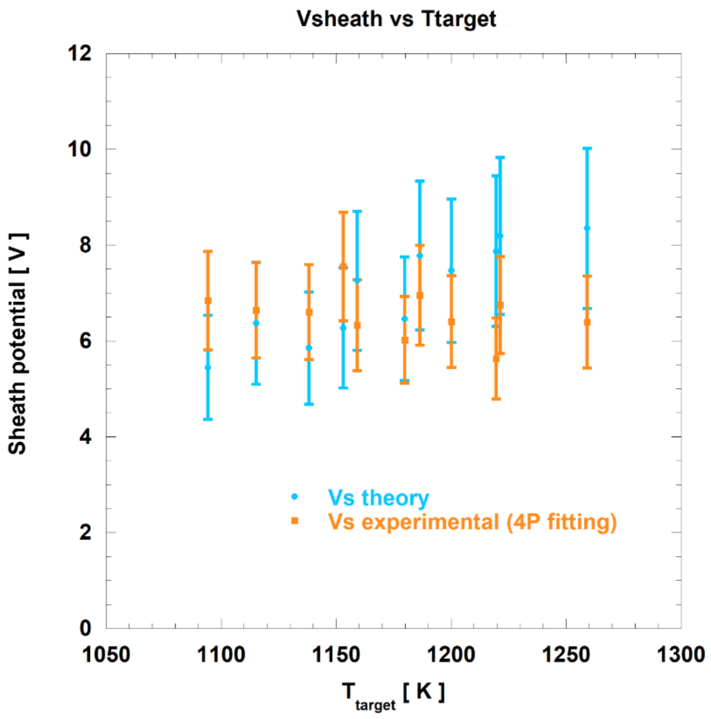
- Theoretical calculation considering collisionless sheath, $Sn^{+}$, $Sn^{2+}$ and $H^{+}$ populations and cold/thermalized ion cases:

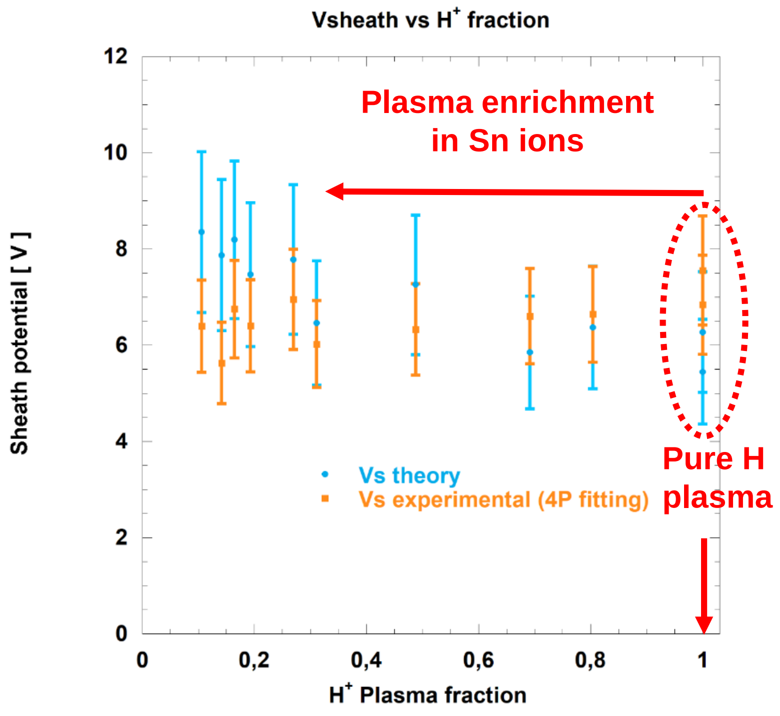
$$V_s = \frac{k_b \cdot T_e}{e} \cdot \ln\left[\frac{\frac{1\ n_e}{a\sqrt{\pi m_e}}}{\frac{n_{Sn+}}{m_{Sn+}} + \frac{2n_{Sn2+}}{m_{Sn2+}} + \frac{n_{H+}}{m_{H+}}}\right]$$

Ti=Te→a=2; Ti<<<Te →a=√2 Comparison to experimental values from determined Vp and Vf.

- **No significant deviations between theory and measurements in studied range (limited by experimental issues)**
- Electron saturation branch and previous analysis affected by confusing **instrumental problems** (e- saturation current overlapping with limits of circuit and amplifier) at T>1300 K, $Sn^{+}$ density>$5\cdot10^{18}$ $m^{-3}$ and $x_{H+}$<10%
- **System upgrade and future experiments to study denser, almost pure Sn plasmas in vapor shielding regimes are ongoing**



# Sn-Sn+ collisionality in vapor shielding state

- Estimation of Sn-$Sn^+$ rate coefficient, cross section (Langevin capture) and mean free path:

$< \sigma v > = 2\pi \sqrt{\frac{C_4}{\mu}}$; $C_4 = \frac{\alpha q^2}{32\pi^2 \varepsilon_0^2}$; $\alpha = 4\pi\varepsilon_0 \alpha_v$; $\sigma_{Sn-Sn^+} = < \sigma v > / \sqrt{\frac{8 k_B T_e}{\pi \mu}}$; $\lambda_{Sn-Sn^+} = \frac{1}{n_{Sn} \cdot \sigma_{Sn-Sn^+}}$ with $\alpha_v$ being the polarizability volume and $n_{Sn}$ the density of evaporated Sn ($T_{target}$ dependent)

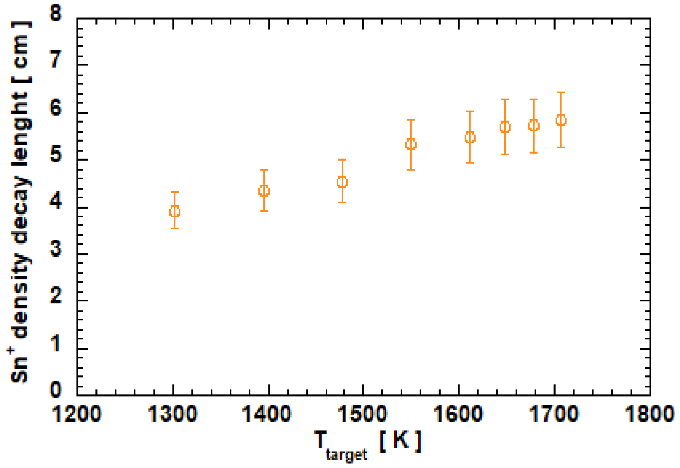
- 16 channel $Sn^{II}$ (645.3 nm) spatial array of $Sn^+$ emission from plasma. Estimation of Sn+ plasma characteristic length:

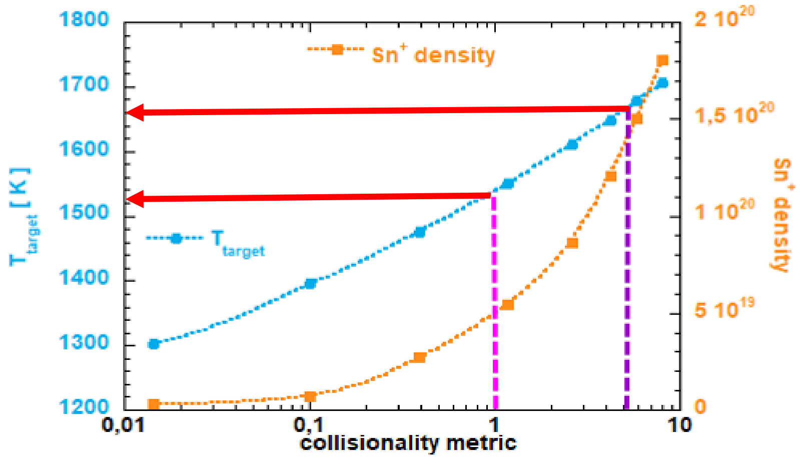
$I(r) = I_0 e^{-\frac{r}{Rp}}$; $I(r) \propto n_e(r)\, n_{Sn}^+(r) \cdot < \sigma v >$; $n_e \propto n_{Sn}^+ \rightarrow n_{Sn}^+(r) = n_{Sn}^+(0) \cdot e^{-\frac{r}{2Rp}}$

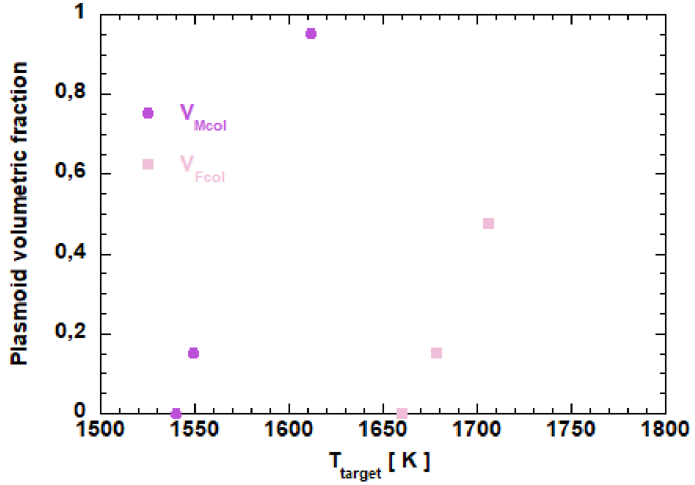
- Collisionality metric defined as: $\xi_{Sn-Sn+} = \frac{2R_p}{\lambda_{Sn-Sn+}}$ variying exponentially with radius (same characteristic length, 2Rp)

- **Whole volume moderately collisional ($\xi_{Sn-Sn+}$>1) and surface boundary fully collisional ($\xi_{Sn-Sn+}$>5) at Ttarget>1650 K and $n_{Sn+}$ >$1.35 \cdot 10^{29}$ $m^{-3}$. Conditions previously identified as vapor shielding onset: (A. de Castro et al. Nucl. Fusion 2025 65 056034)**

- **Whole characteristic volume would be fully collisional at Ttarget>1760 K. Coincides with previous steady-state regime (1775 K)**



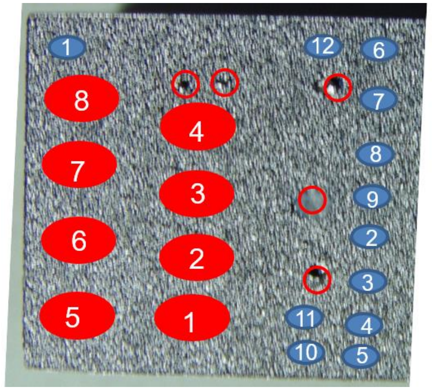



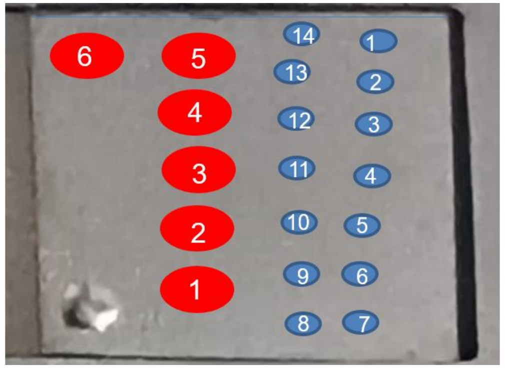
# Sn/Li wetted W CPS High-energy laser exposure experiments

# Studied targets: Previously exposed to NBI

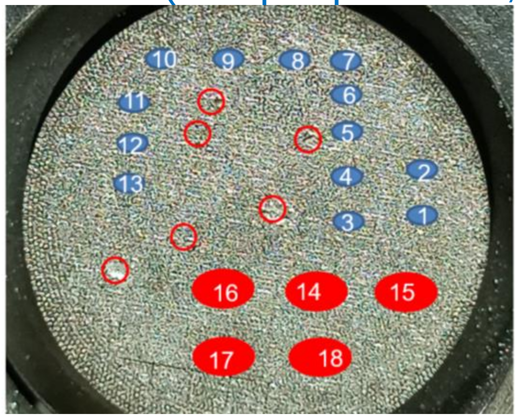
AUG Ref_W
(30 µm pore size, 37% porosity, non wetted)

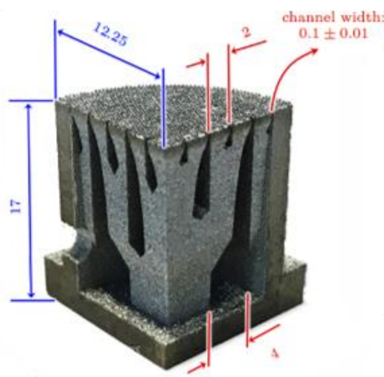


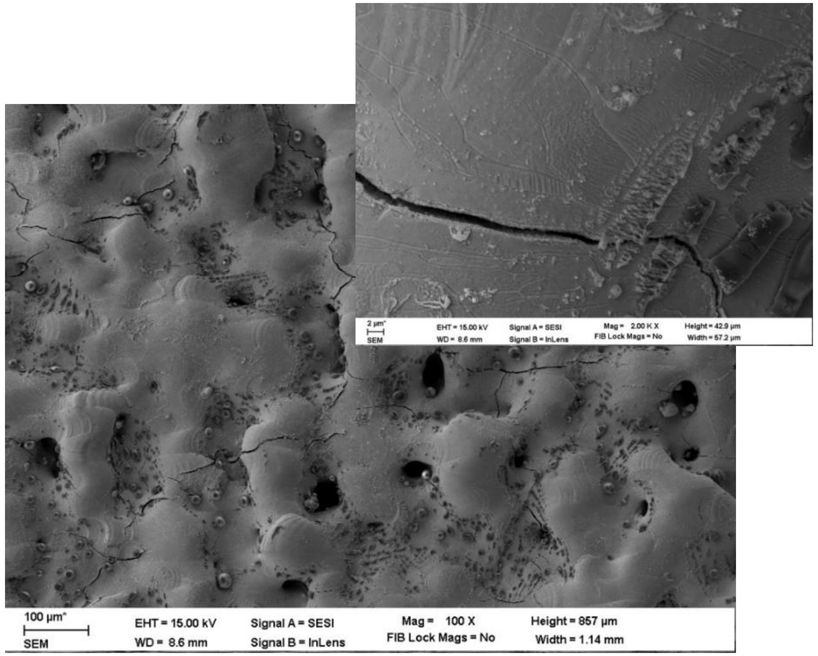

AUG W_Sn
(30 µm pore size, 37% porosity)

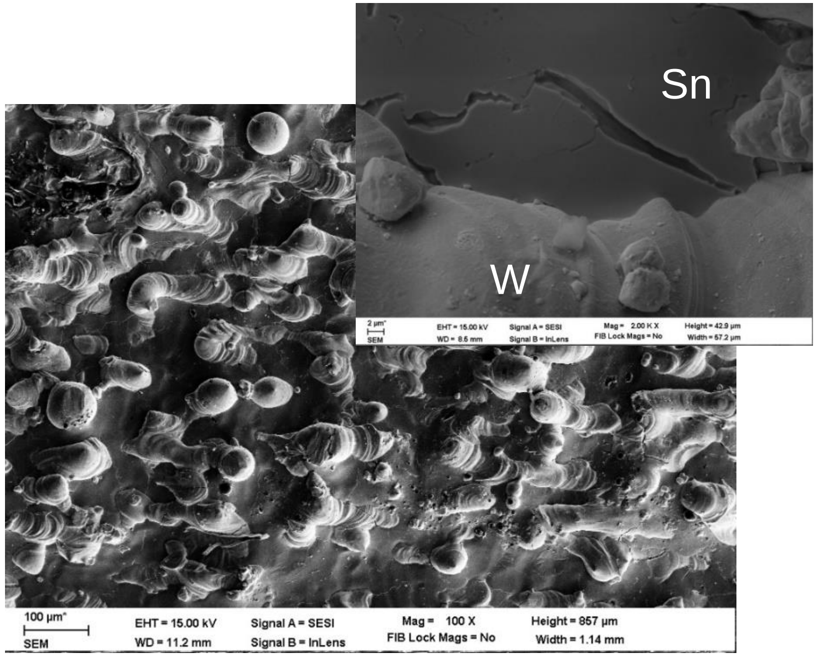


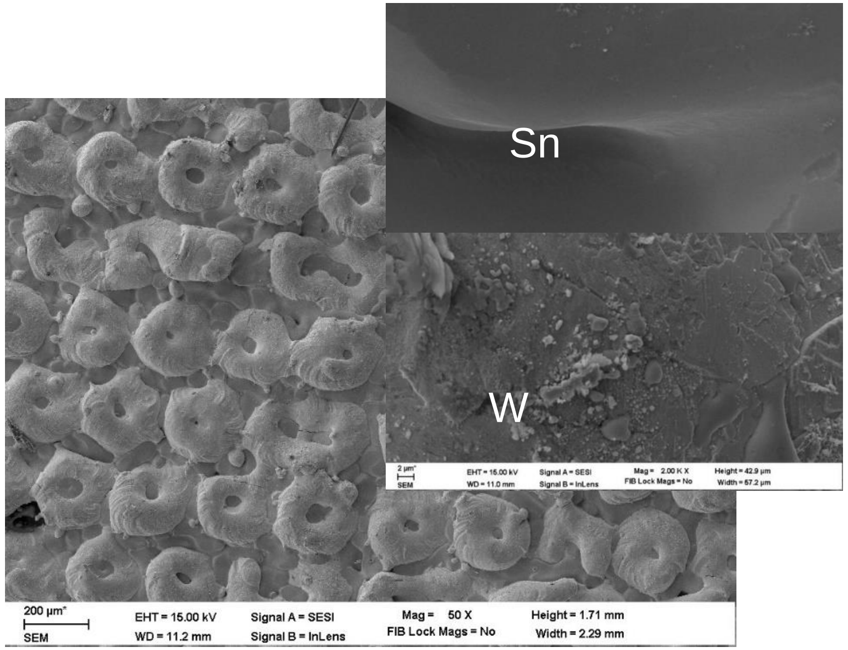

3D printed W_Sn
(100 µm pore size, rewetted)



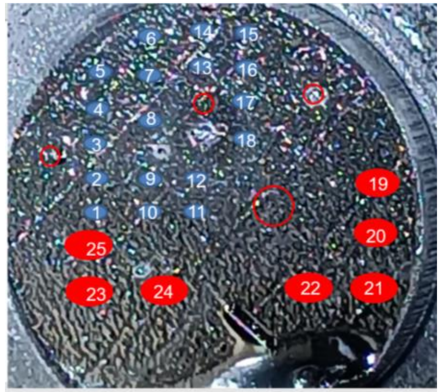



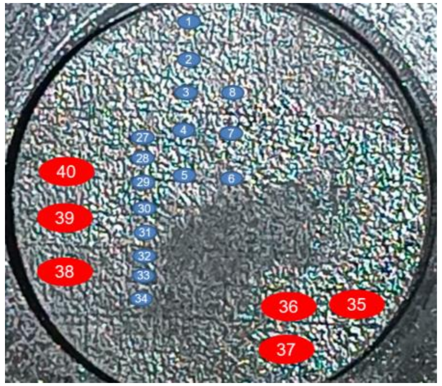



# Studied targets: Varying porosity targets

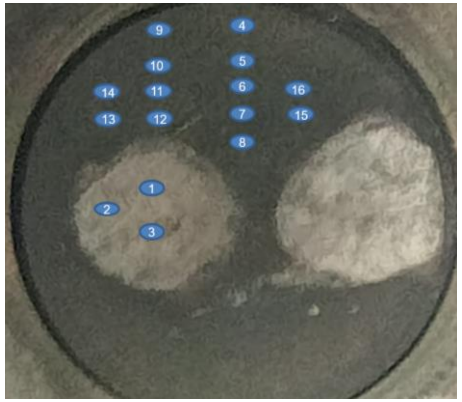
## AENIUM C2_1
(superficial wetting)



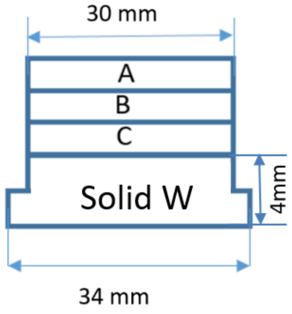
## AENIUM C2_2
(Wetted at DIFFER, 67% filled with Sn)



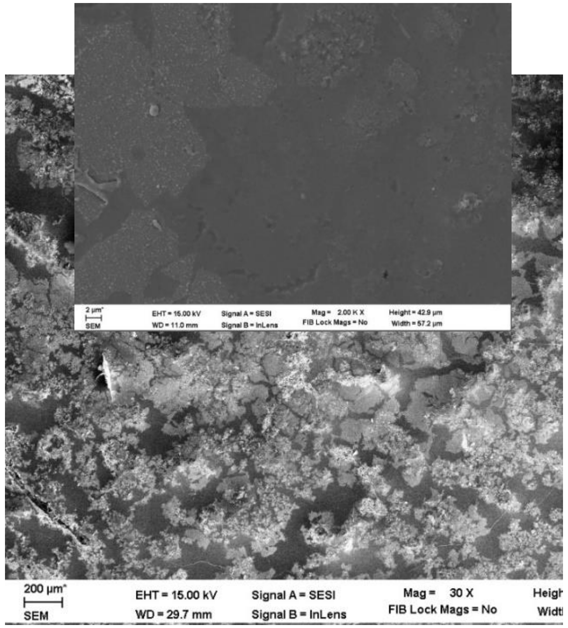
## AENIUM C3_2
(50% filled with **Li** in OLMAT)



| C_2 | | | |
|---|---|---|---|
| Layer | Thickness (mm) | Mean porosity (mm) | % Porous volume |
| A | 1 | 50 | 28 |
| B | 3 | 300 | 43 |
| C | 0 | N/A | |
| **C_3** | | | |
| Layer | Thickness (mm) | Mean porosity (mm) | % Porous volume |
| A | 1 | 50 | 28 |
| B | 1 | 300 | 43 |
| C | 2 | 500 | 50 |

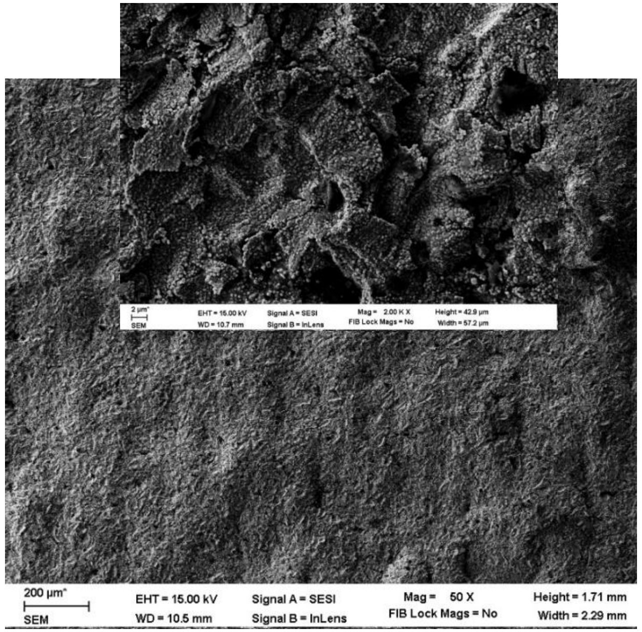



## AENIUM C2_1

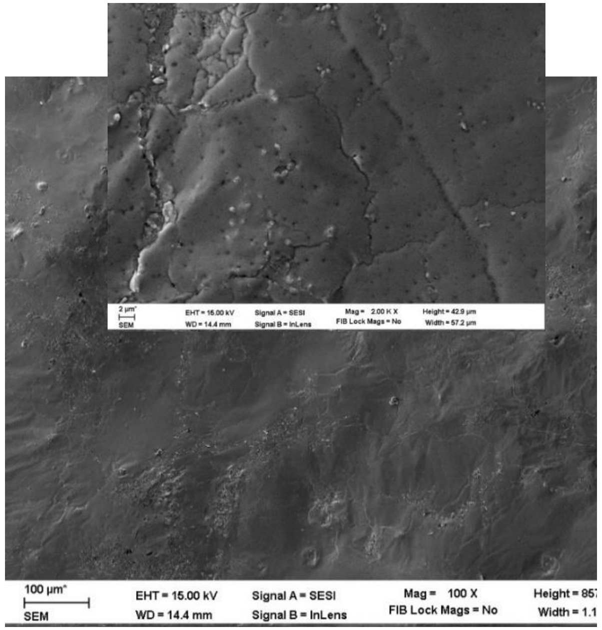



Non wetted area

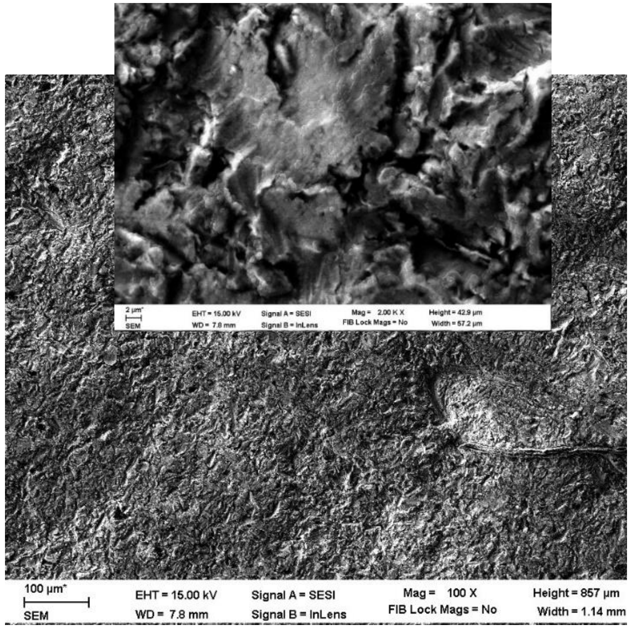
## AENIUM C2_2




Wetted area



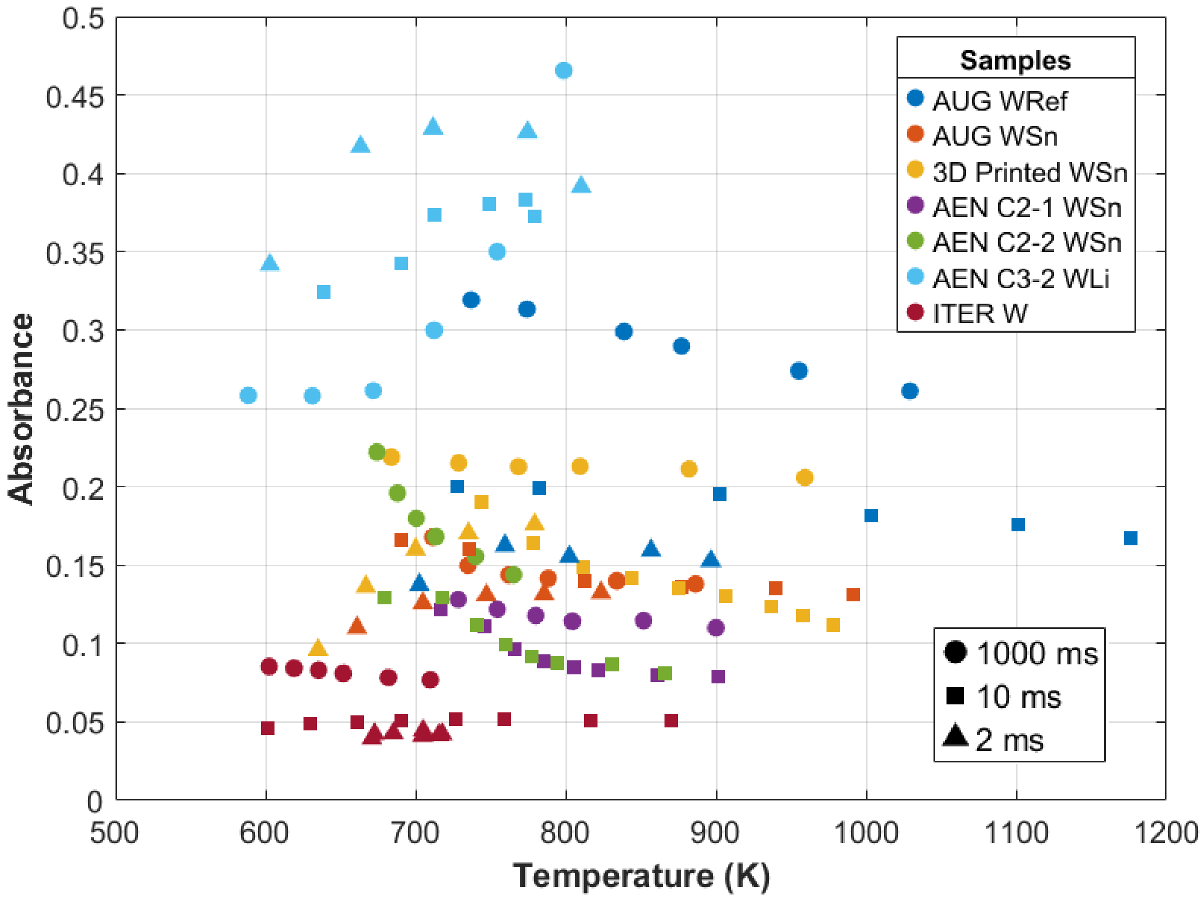

## AENIUM C3_2



# Absorbance measurements

Laser spot area: 46 mm$^2$ (9.75 mm x 6 mm), pyrometer spot diameter: 6 mm.
Fast camera to assure pyrometer and laser spot **overlap**.
1 s, 10 ms and 2 ms pulses with increasing power → Absorbance obtained through fitting of temperature increase to simulations (P. Fernandez-Mayo)

- Li sample shows **increasing absorbance values**; all others (liquid Sn, W) generally **decrease** with temperature.
- W samples vary significantly based on **surface roughness** (7% for polished ITER W vs. 23% for porous AUG W-Ref), while liquid Sn generally ranges between 10–20%.
- **First reported measurements** for liquid Li, no references found to compare with.



# Particle ejection on set (PEO)

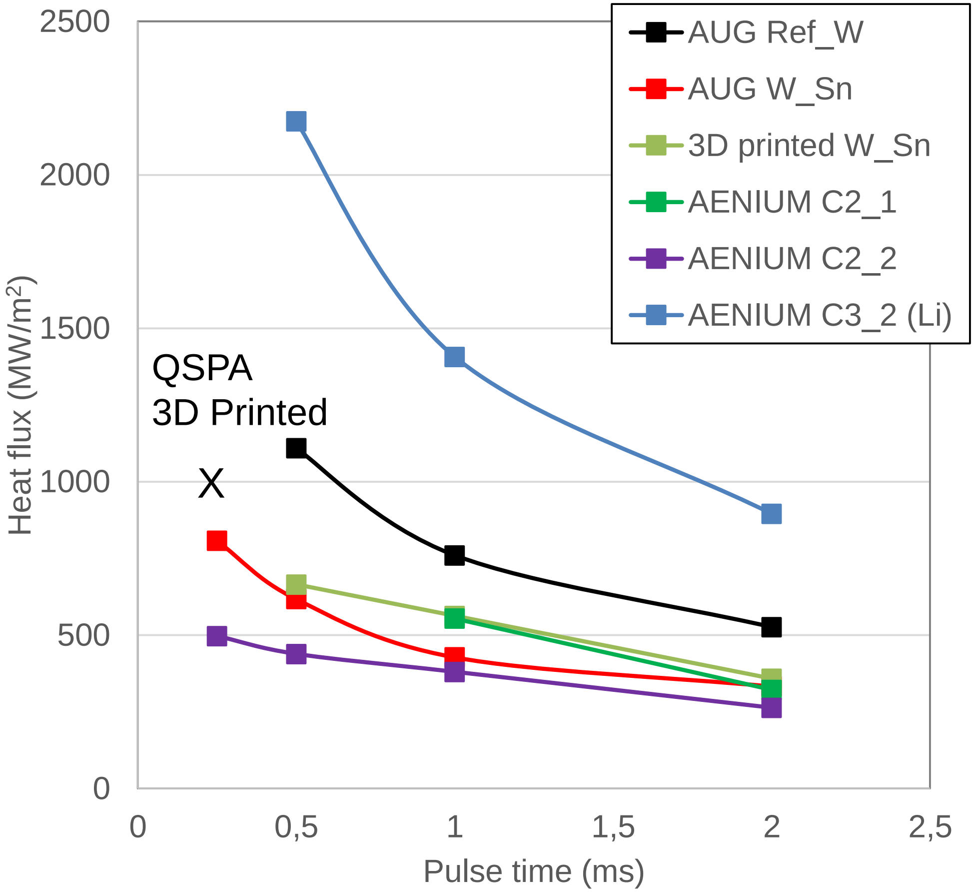
Particle ejection on set (PEO) for different pulse times at $T_i$=300 ºC (2 ms, 1 ms, 0.5 ms, and 0.25 ms):

- 100 µm fiber and 750 mm lens→ Area 1.3 mm$^2$ (1.62 mm x 1.0 mm)
- Consecutive shots with 10% increment power up to maximum power (4 spots).
- Changing spot positions around PEO value obtained in previous shots (around 8-12 spots)

Heat flux values calculated with the experimentally obtained absorbance values (2 and 10 ms measurements mean values):

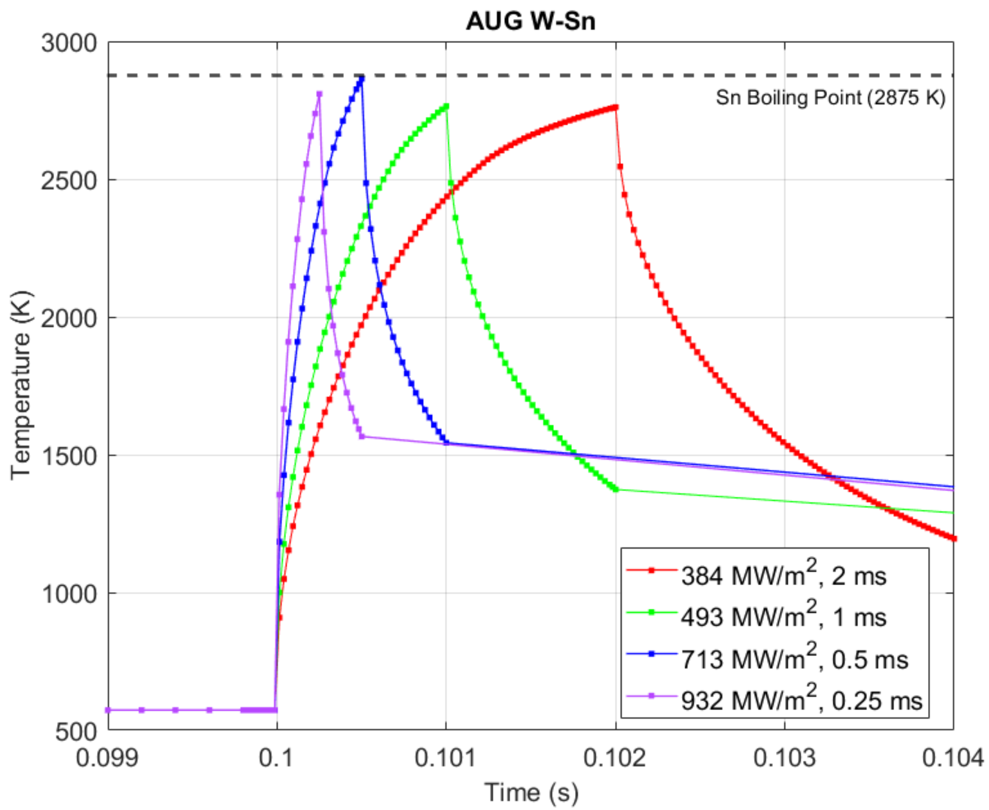
| AUG Ref_W | AUG W_Sn | 3D printed W_Sn | AENIUM C2_1 | AENIUM C2_2 | AENIUM C3_2 (Li) | ITER-like W |
|---|---|---|---|---|---|---|
| 0,16 | 0,13 | 0,14 | 0,08 | 0,08 | **0,35** | 0,07 |

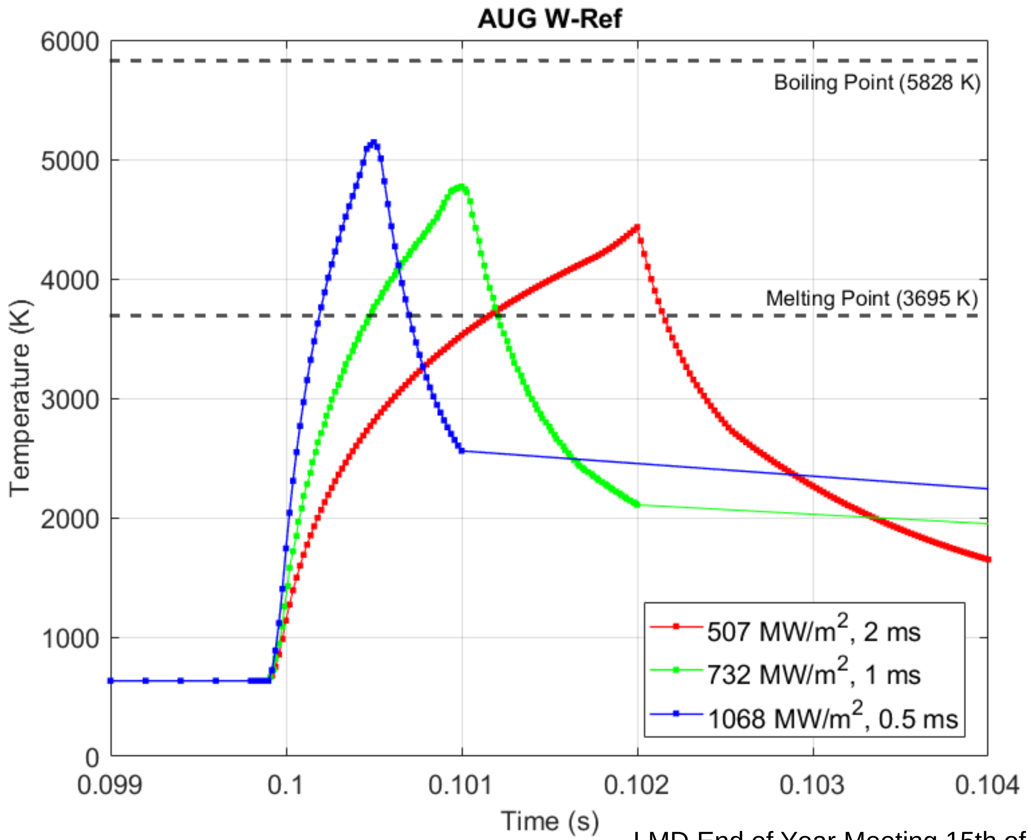
- For ITER-like W targets no particle ejection was observed even at the highest laser power (510 MW/m$^2$)
- Increasing PEO values for decreasing pulse time.
- Highest PEO values for Li-wetted target (higher absorbance value as well).
- Higher PEO values for non-wetted W target.



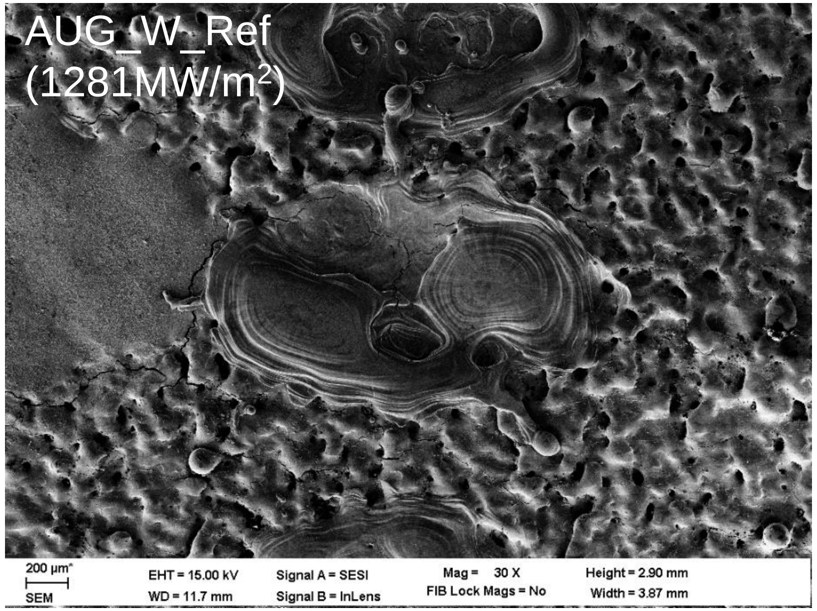
# Particle ejection on set (PEO) surface temperature

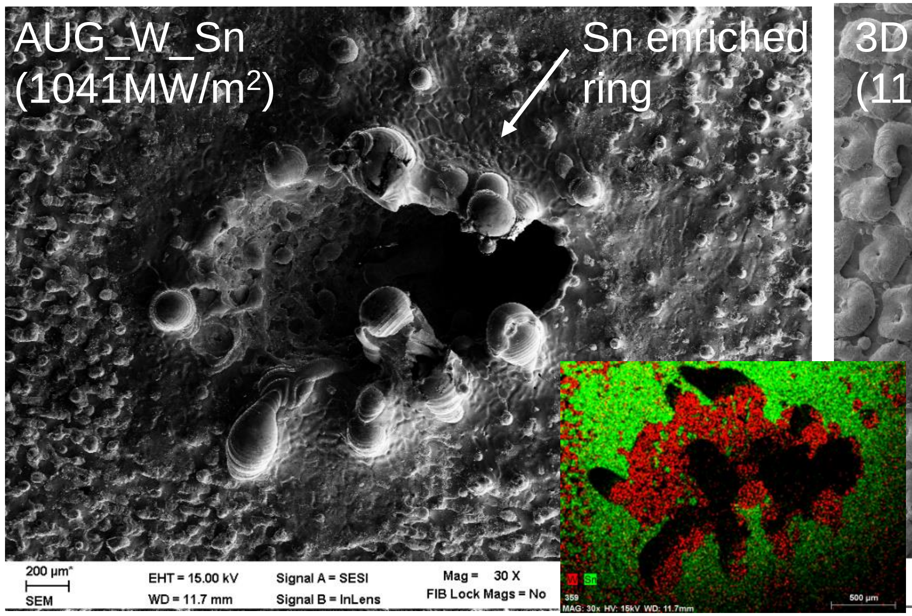
- Pyrometer **underestimates** temperatures due to spot size → Thermal simulations needed to estimate temperatures
- **Fixed absorbance** value: 0.15 for AUG W-Ref and AUG W-Sn: Errors in estimating the PEO heat flux values.
- AUG W-Sn: Maximum temperatures close to Sn boiling point → Particle ejection due to possible **surface boiling**
- AUG W-Ref: Temperatures surpass W melting point → Liquid pool ejecting particles due to **local boiling points**

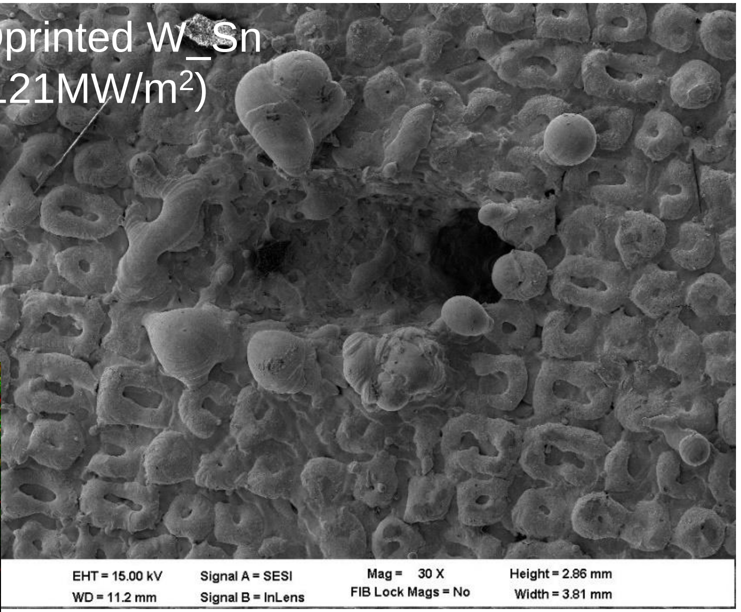


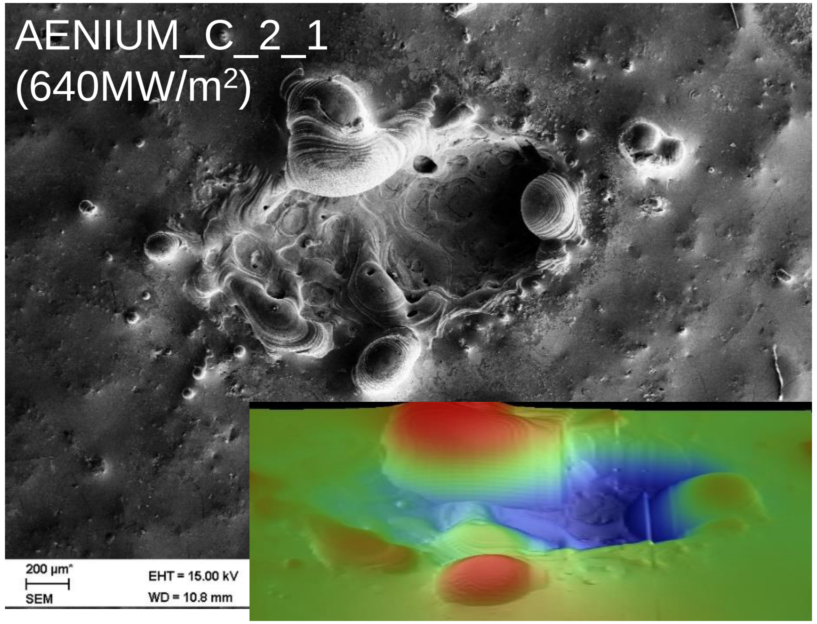



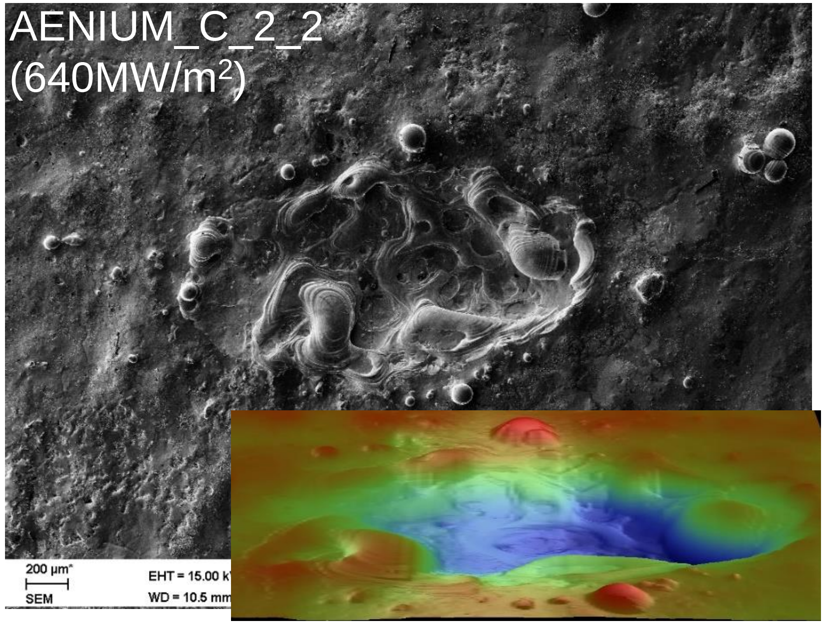
# Crater characterization: 2 ms up to max

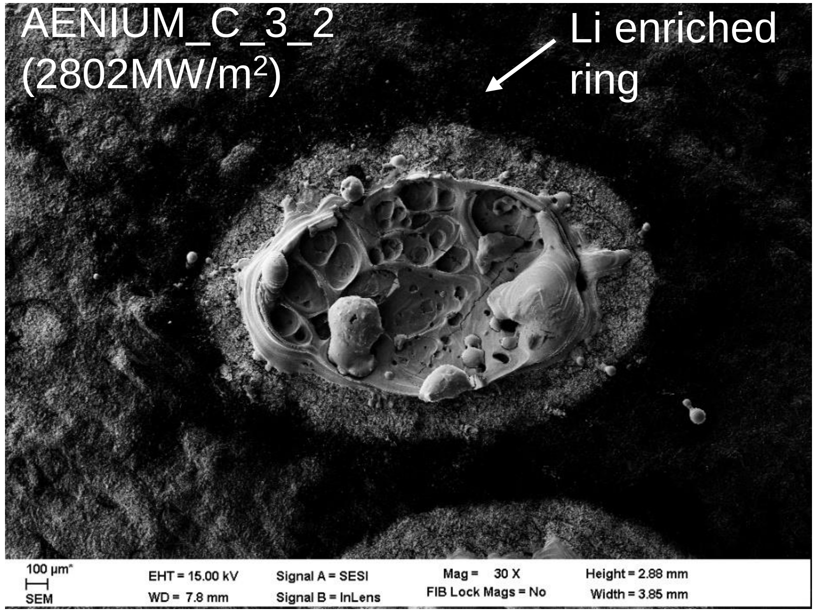


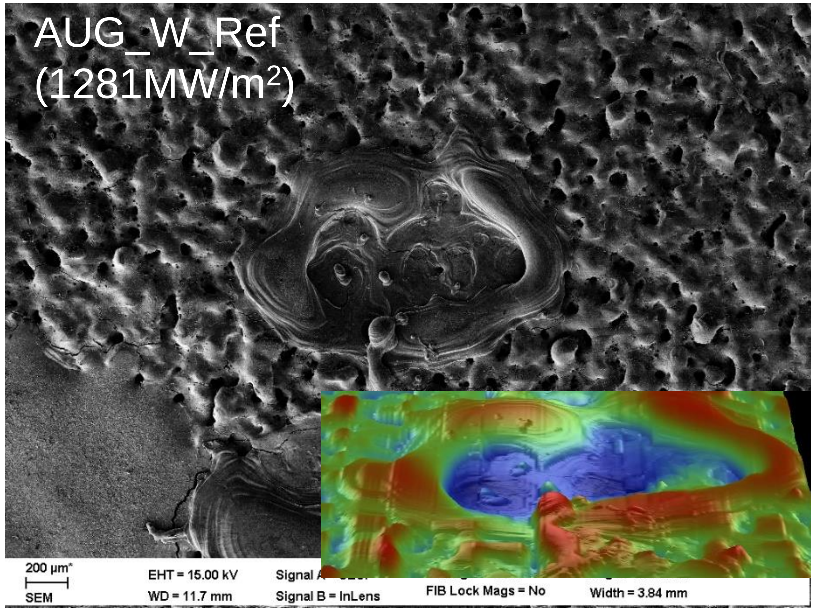



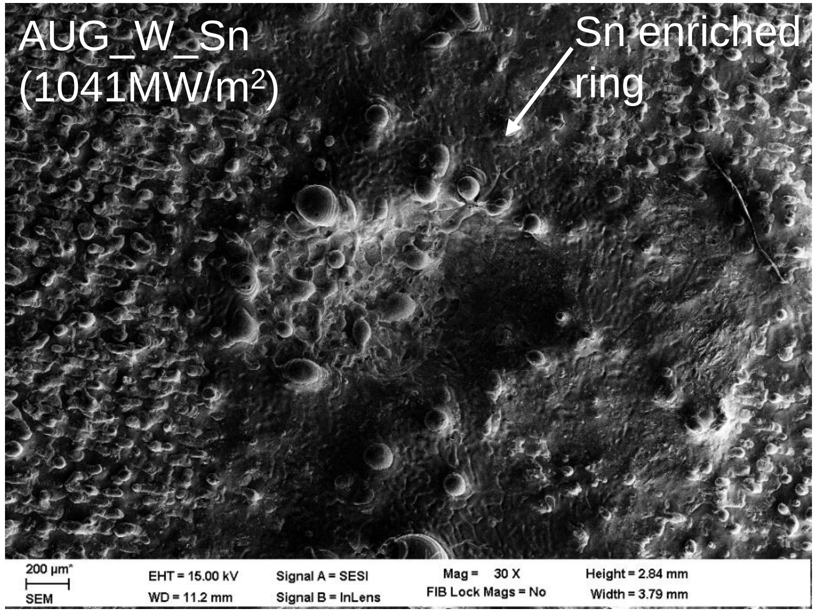



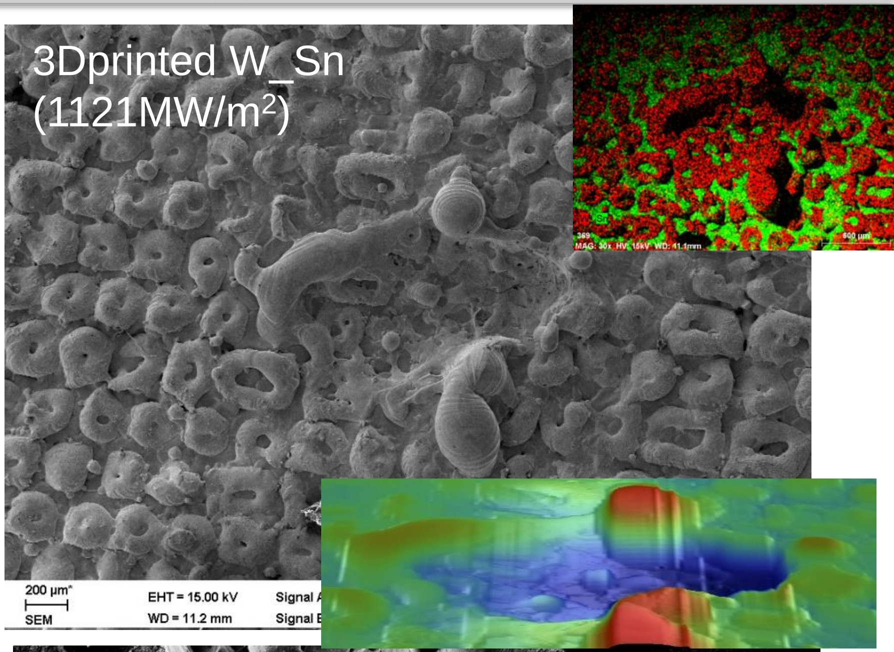



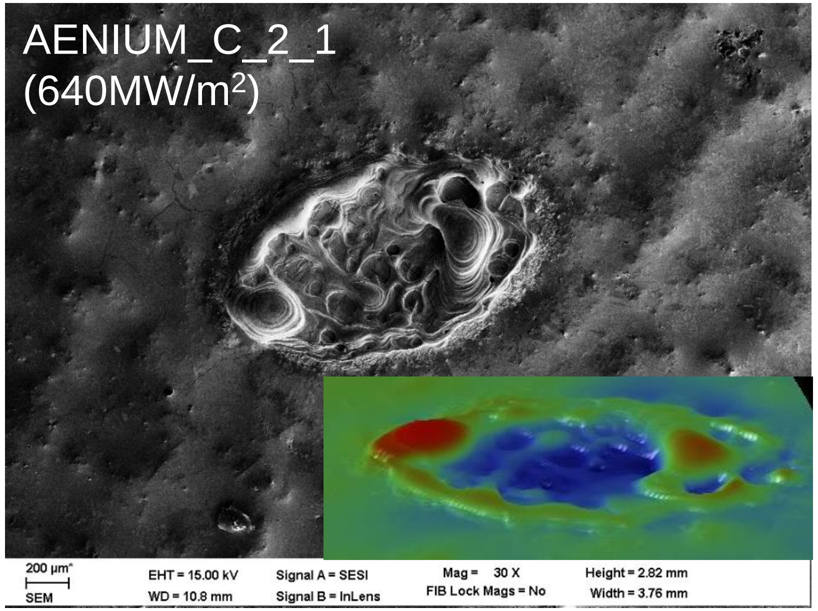



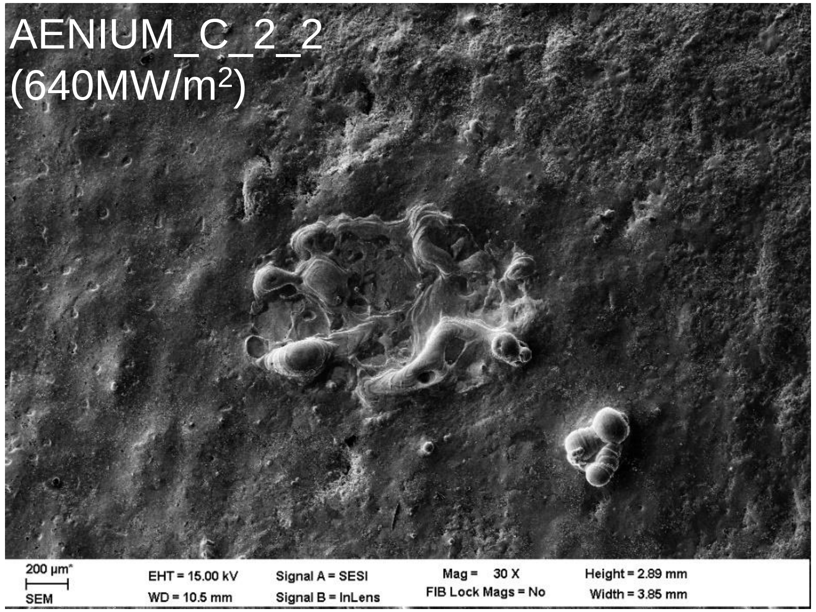
# Crater characterization: 1 ms up to max

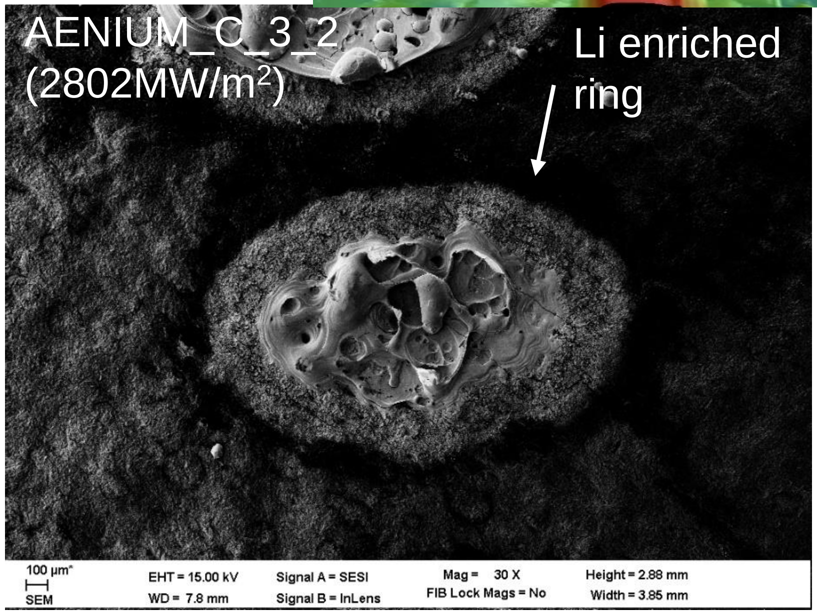


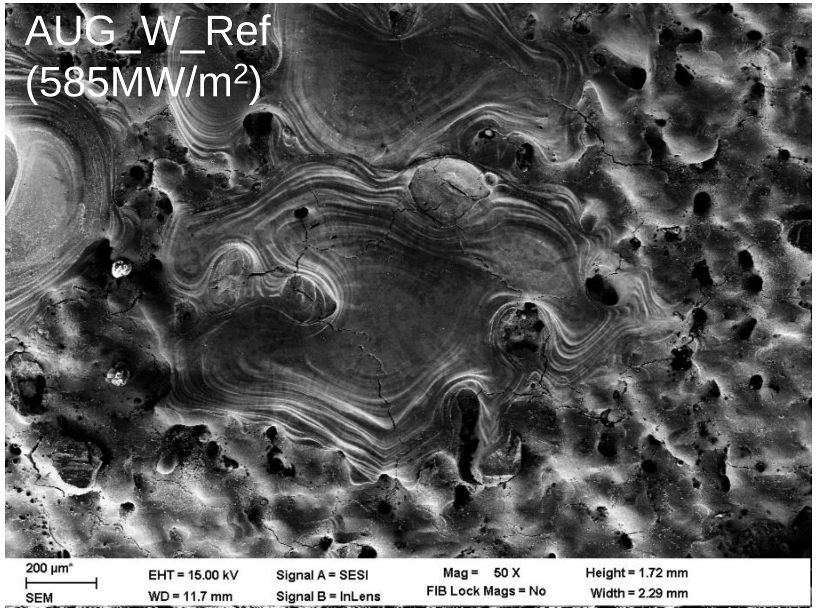



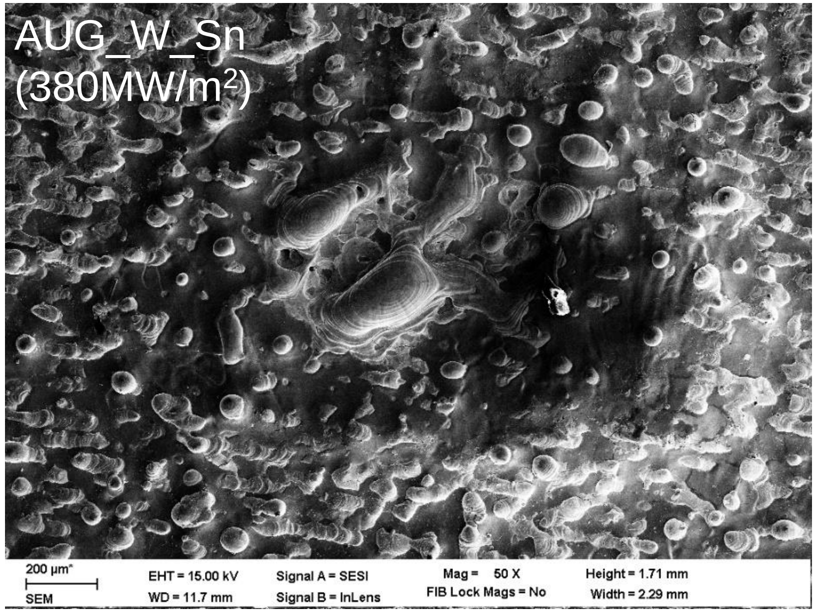



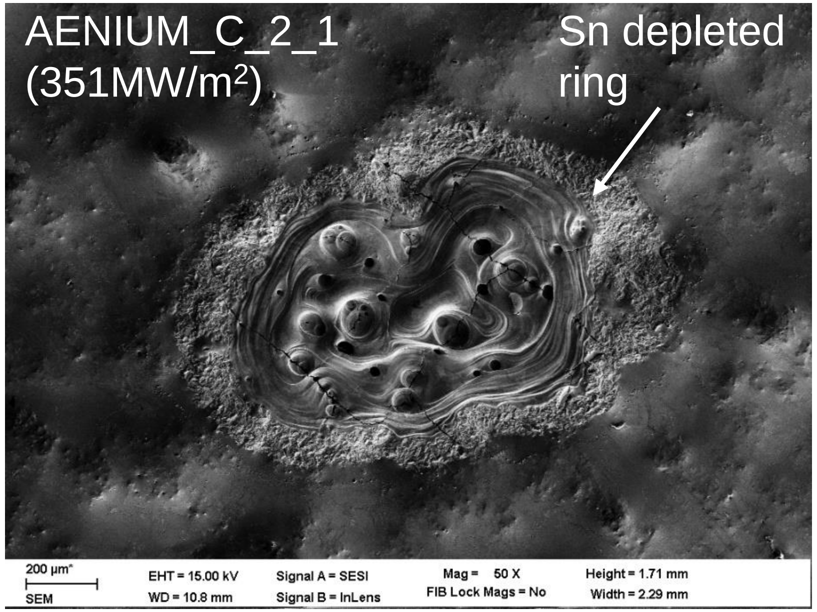



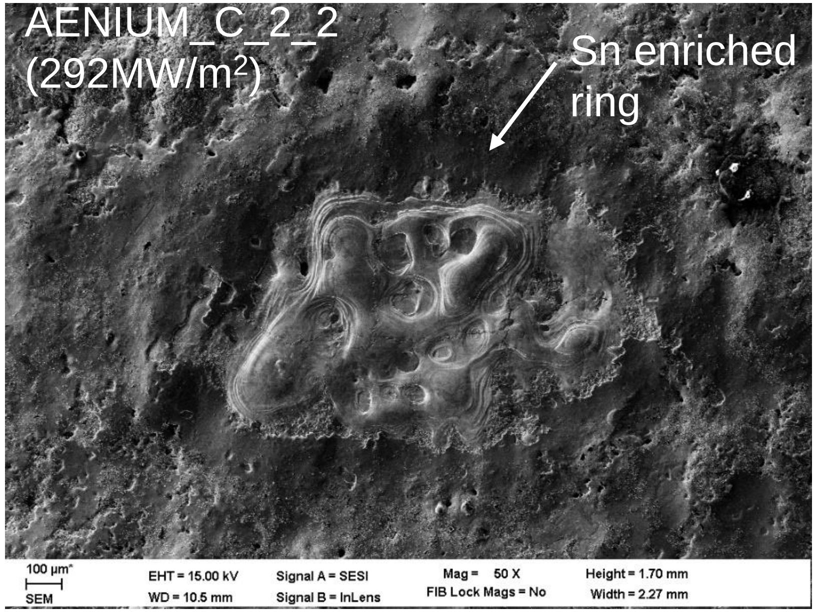



# Crater characterization: PEO 2 ms

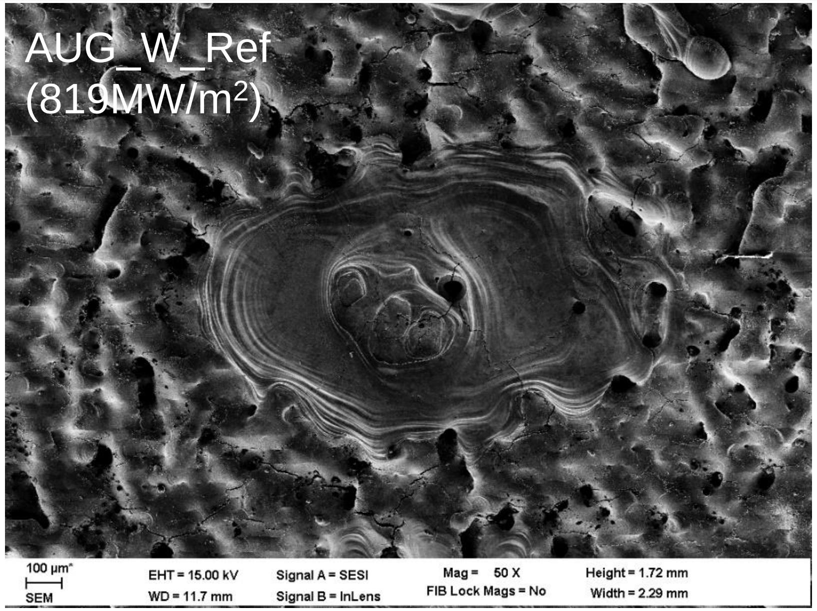


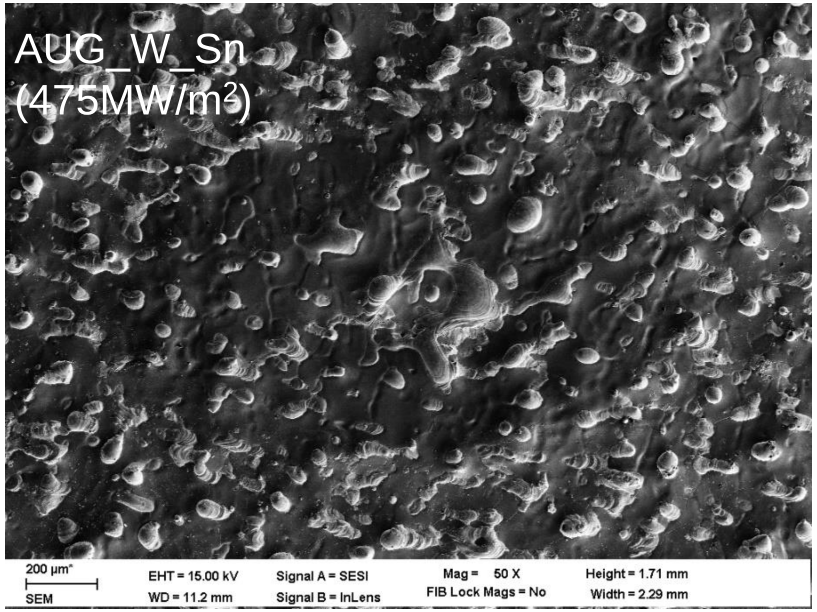



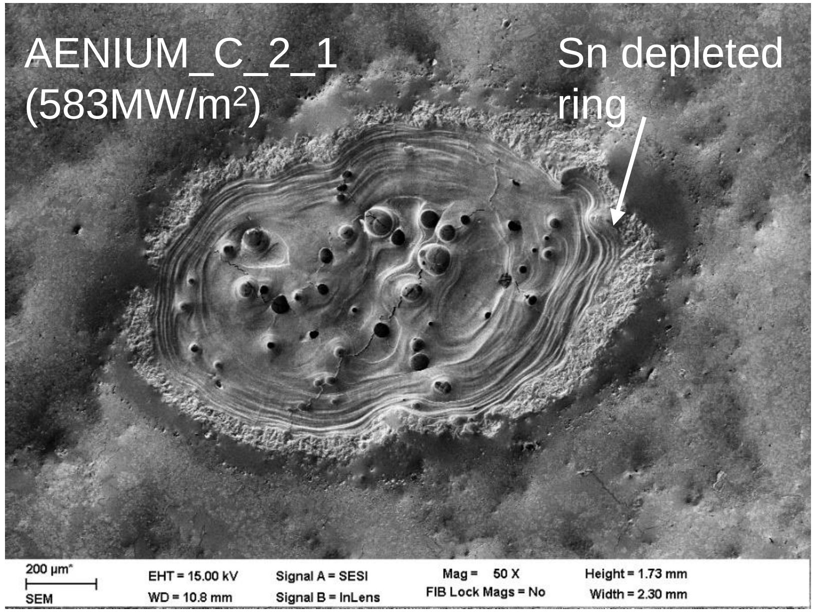



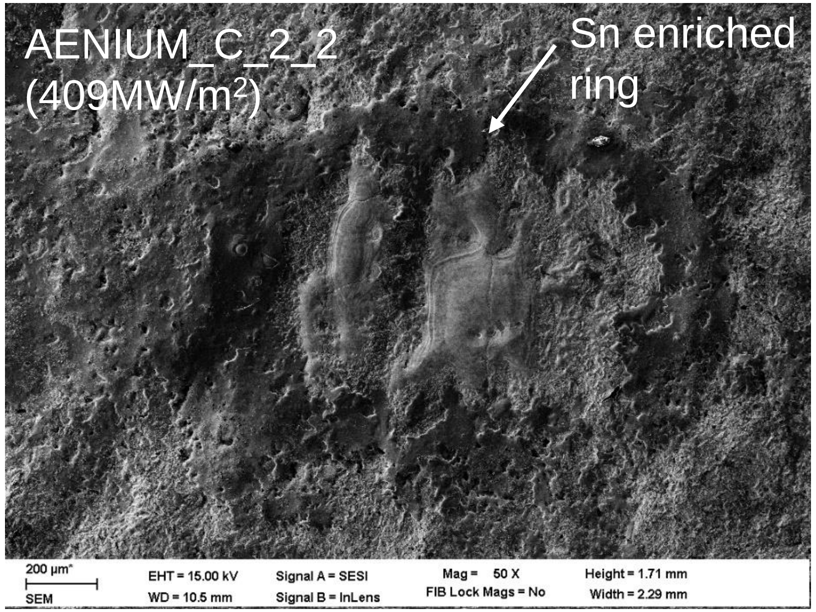



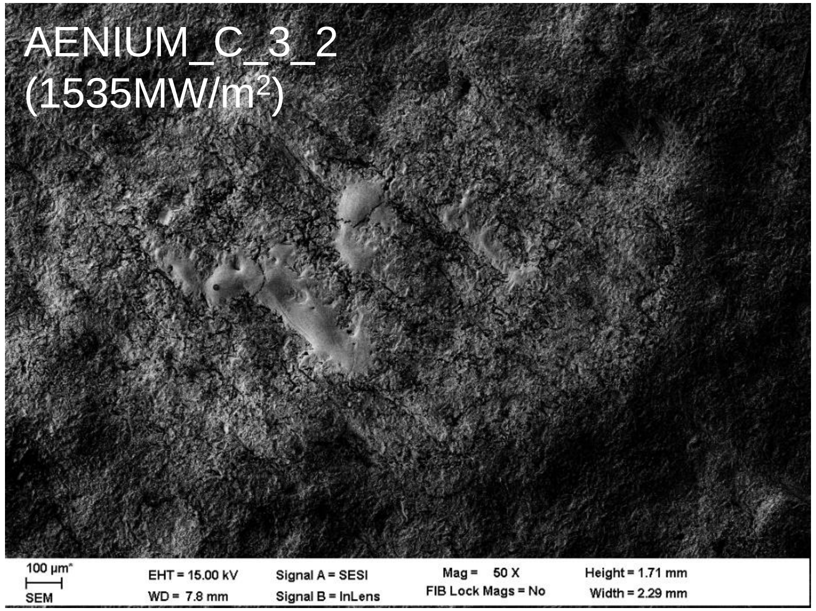

# Crater characterization: PEO 1ms



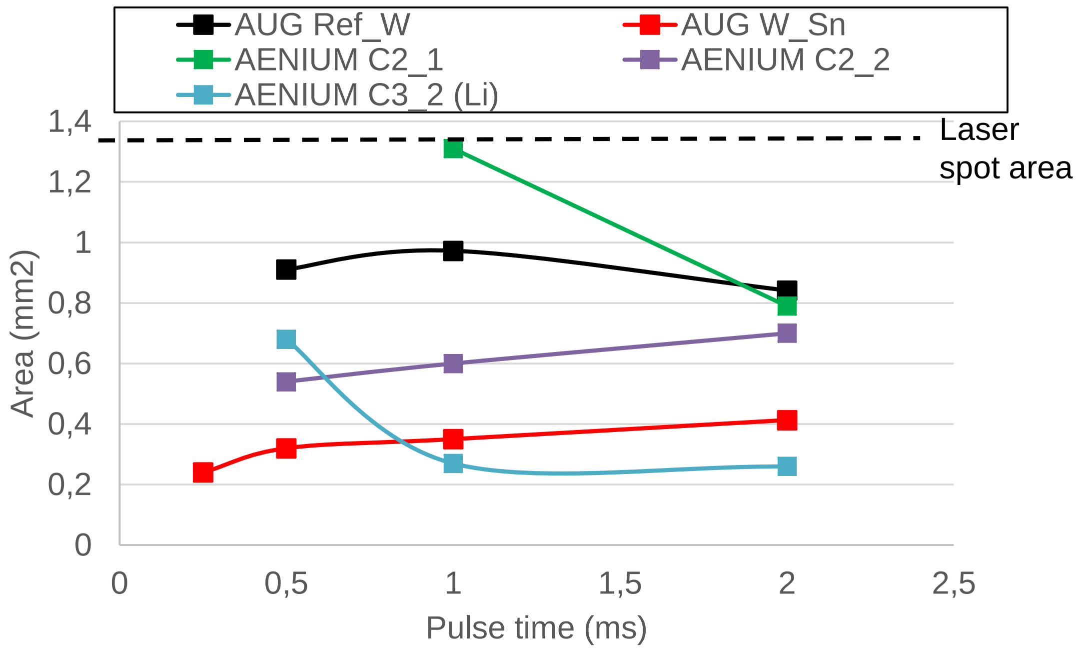



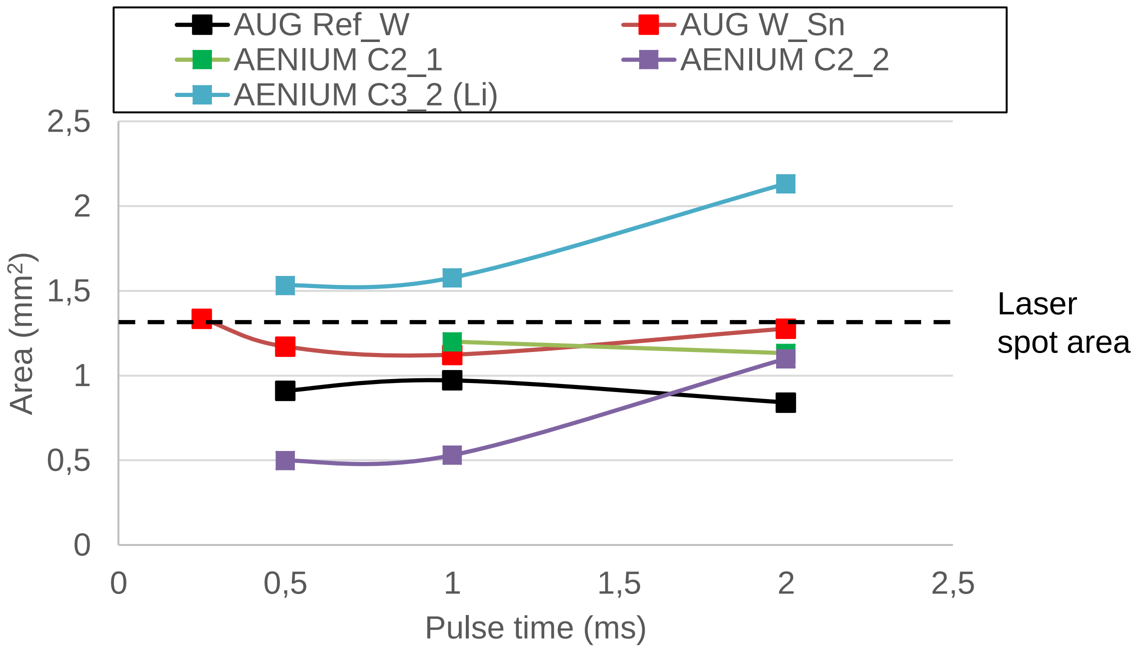



# Crater characterization: Crater size for PEO

## Melted W area



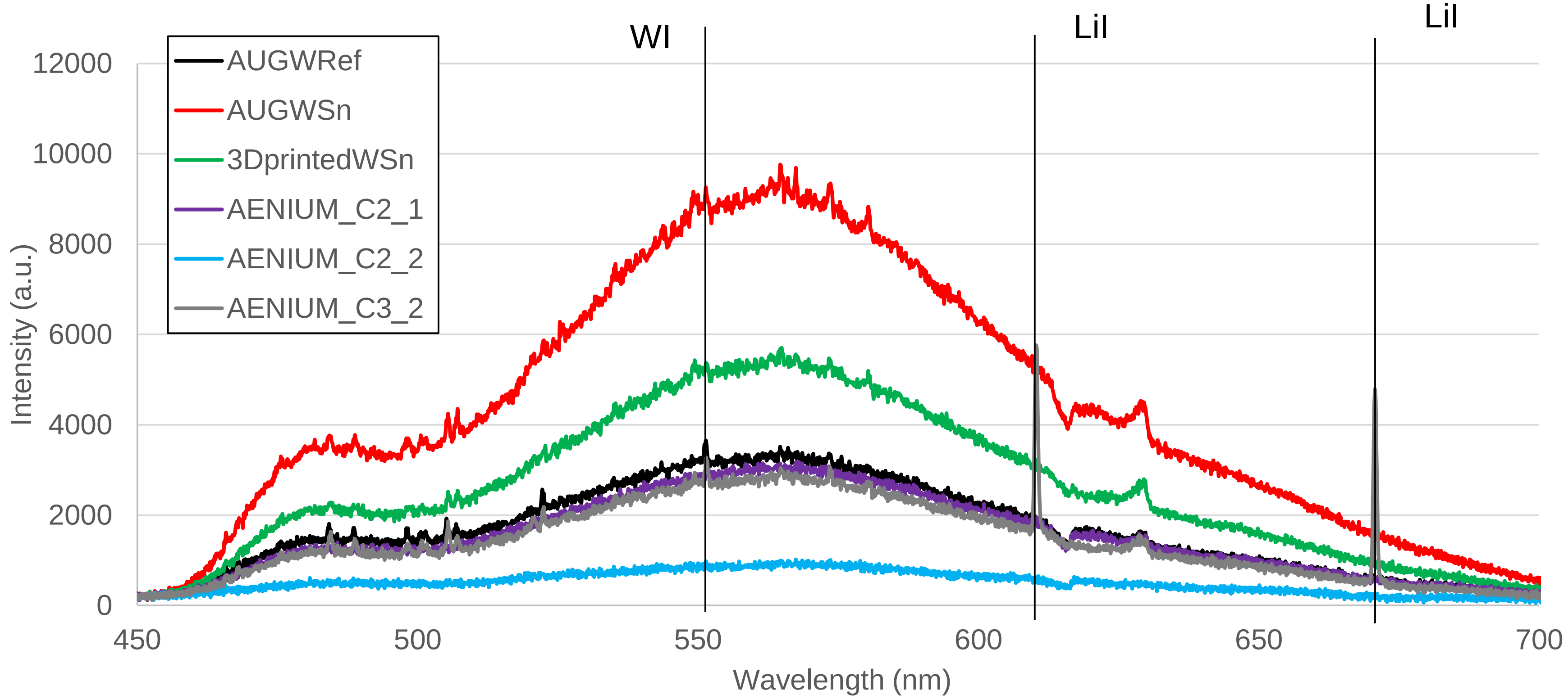

## Complete Crater (affected area)




- **Smaller W melted area** for Sn and Li-wetted targets (except for AENIUM C2_1).
- **No damage** observed for the 3D Printed W_Sn target at PEO heat fluxes.
- **Larger affected area** than laser spot for Li-wetted target: lateral heat transfer and Li evaporation?

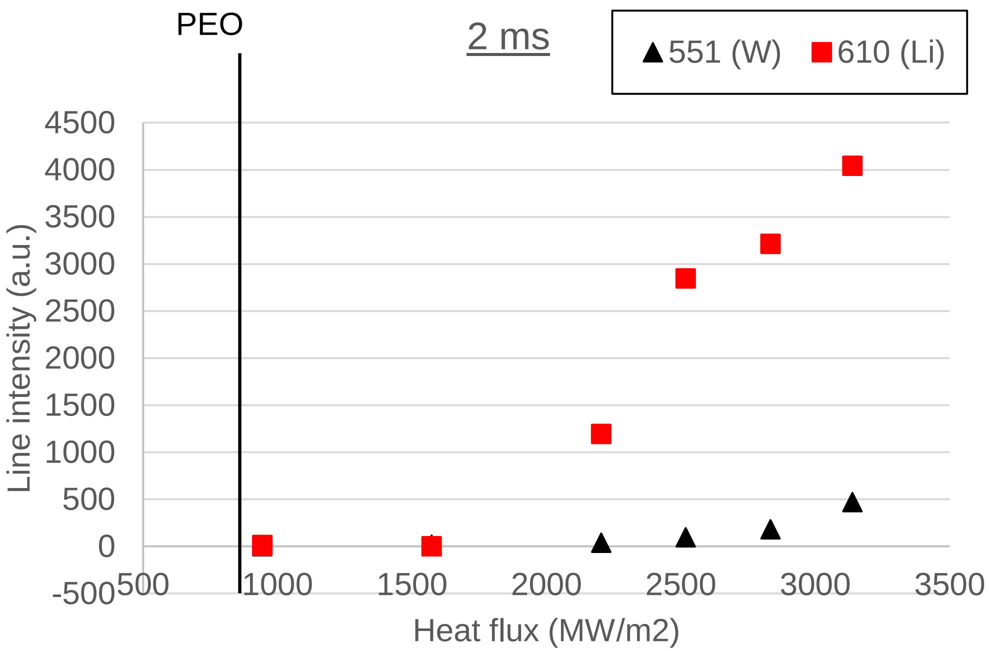
# Spectroscopic results

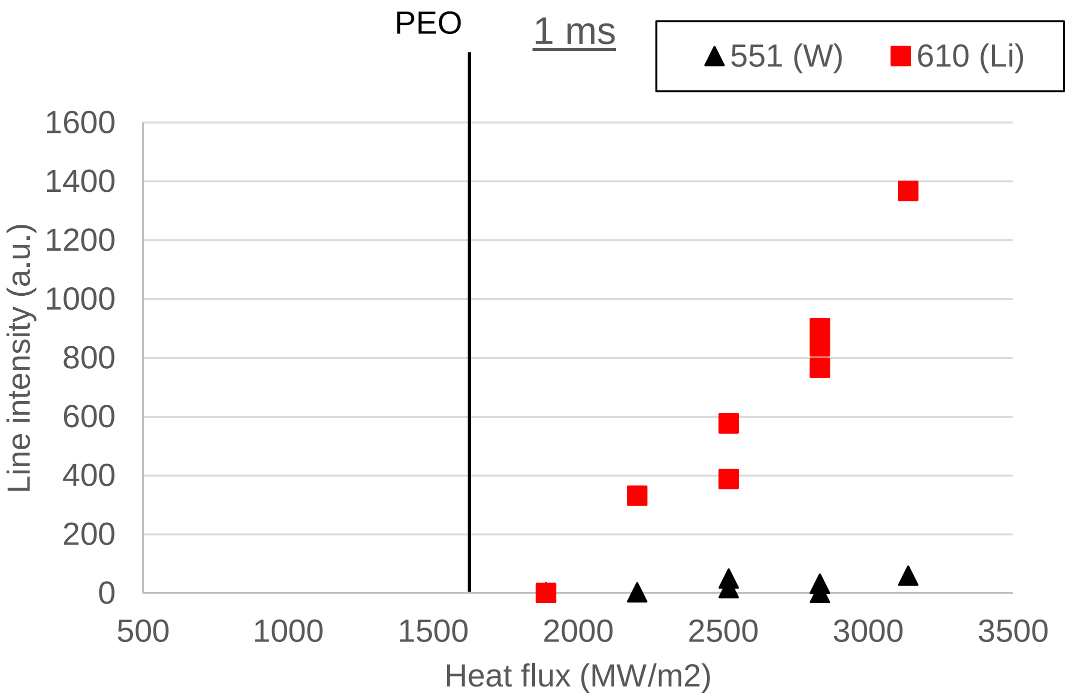
## Highest laser power




- ➢ Very small signal for Sn and W in Sn-wetted W targets→ Not possible to clearly distinguish between W and Sn lines.
- ➢ For Sn targets W and Sn lines are observed simultaneously for the same laser powers (previous results).
- ➢ Li-wetted W target→ Distinguishable Li and W lines.

# Spectroscopic results: Li



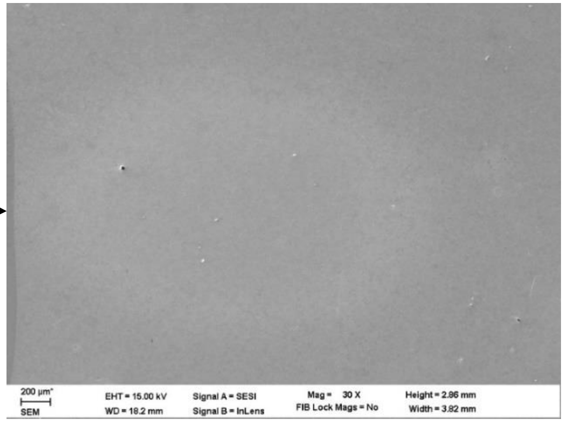
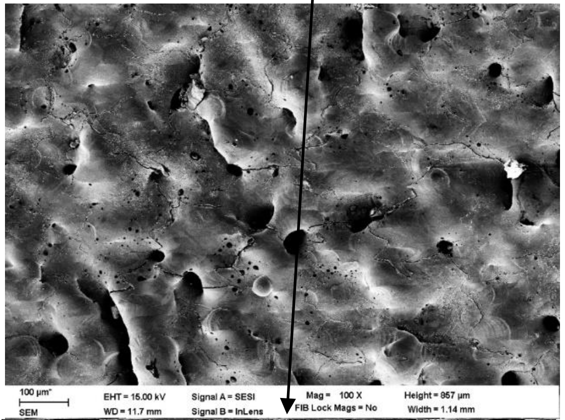
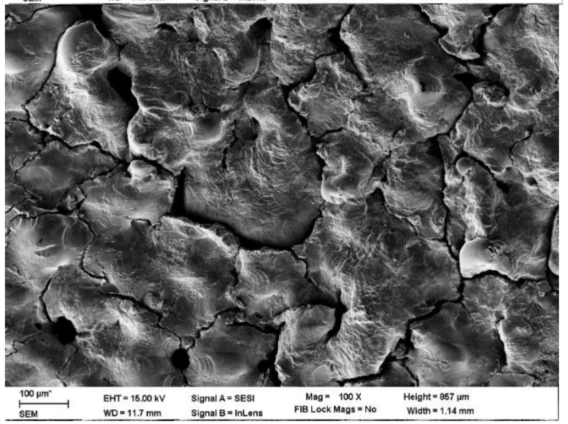
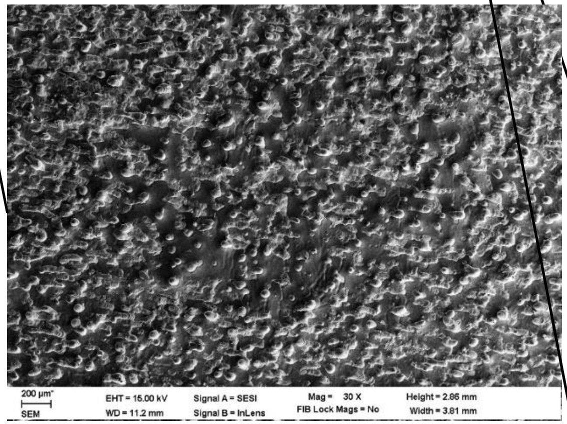
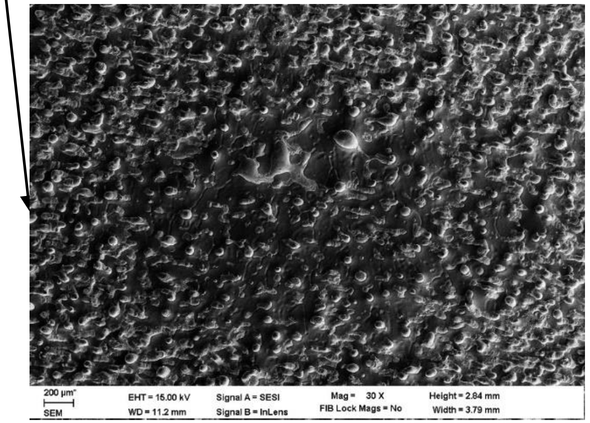
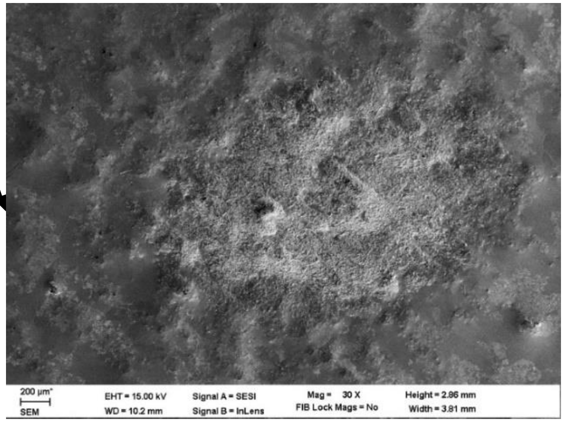
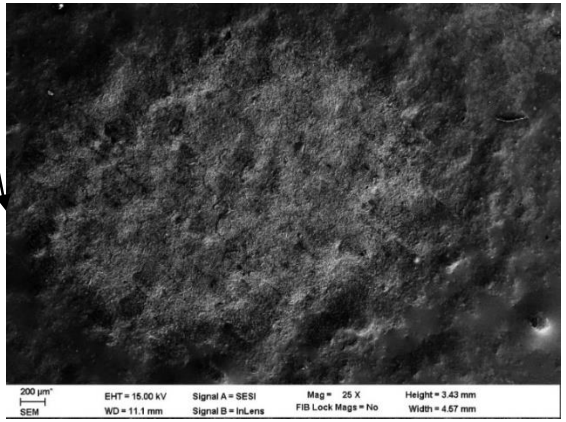
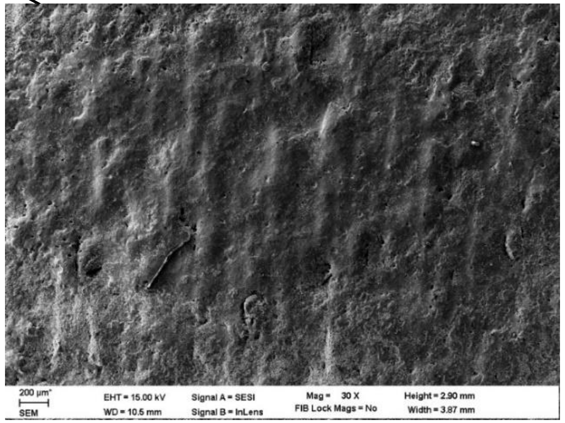




- For the case of Li, preferential **Li ejection** is observed for **lower heat fluxes**.
- This could indicate **better refilling** and thus, **better protection** of the substrate with Li than with Sn.

# High frequency exposure

Studied heat fluxes (MW/m²) for 1 ms 50 Hz pulses

| Number of pulses | AUG Ref_W | AUG W_Sn | 3D printed W_Sn | AENIUM C2_1 | AENIUM C2_2 | IterlikeW |
|---|---|---|---|---|---|---|
| 1000 | 53 | 104 | 112 | 64 | 64 | 87 |
| | 107 | 156 | 168 | 96 | 96 | 131 |
| | 213 | X | X | 145 | 145 | 199 |
| 2250 | X | X | X | 145 | X | 199 |
| 10000 | 53 | 104 | 112 | 64 | 64 | 87 |
| | 107 | 156 | 168 | 96 | 96 | 131 |
| | 160 | X | X | X | X | X |
| | 213 | X | X | X | X | X |
| 50000 | X | 104 | 112 | 64 | 64 | 87 |

# Plans for 2026

Deliverable: Experimental testing of mock-ups for COMPASS-U/variable porosity CPS targets (4 operational days).

Expose mock-ups for COMPASS-U to OLMAT if they are delivered to us.

Continue research on **varying in depth porosity** W CPS, either with Sn and Li.

- Collaboration with AENIUM to fabricate these type of targets ongoing.
- Exposure of the Sn/Li wetted targets to OLMAT NBI and laser pulses.

**Sn plasmoid characterization** in ELM-like+OLMAT beam pulses:

- Experiment to scan transient load to discern the effect of particle ejection on local plasma
- Complete analysis of plasma sheath (transmission factor, thickness, collisional effects…)

Exposure of Li targets to transients in collaboration with CPMI-Illinois

- CPMI within research team (National Project). Final schedule will depend on availability/MOU timing

Start works on **OLMAT upgrade** for actively cooled Li targets.

# Thank you!