Plasma characterization of tin-enriched clouds generated during the exposure of a Liquid-Tin Capillary Porous System target at the OLMAT High Heat Flux facility

A. de Castro, E. Oyarzábal, K. J. McCarthy, D. Tafalla, D. Alegre, M. Iafrati, I. Voldiner, F. L. Tabarés and the OLMAT team

65th APS-DPP, Denver-Colorado, October 30-November 3, 2023

Laboratorio Nacional de Fusión
Ciemat

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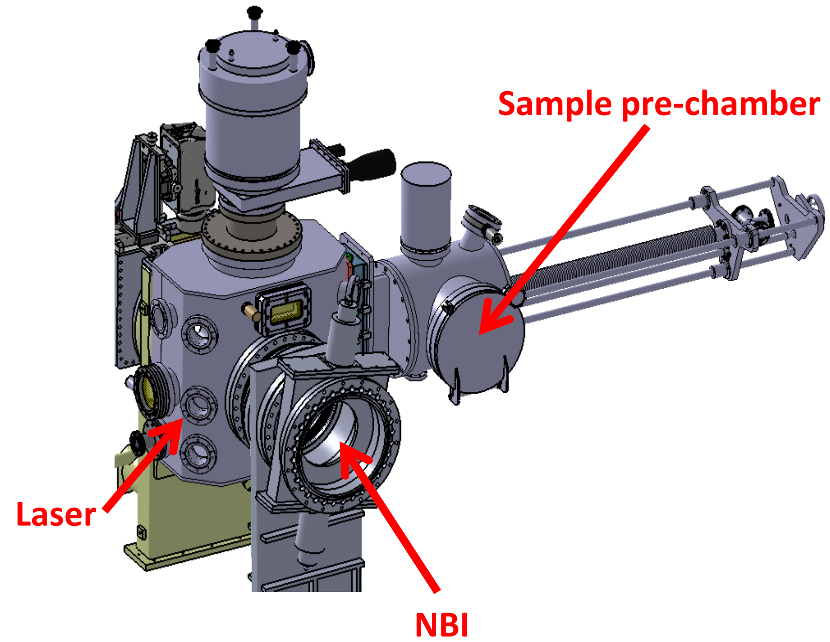
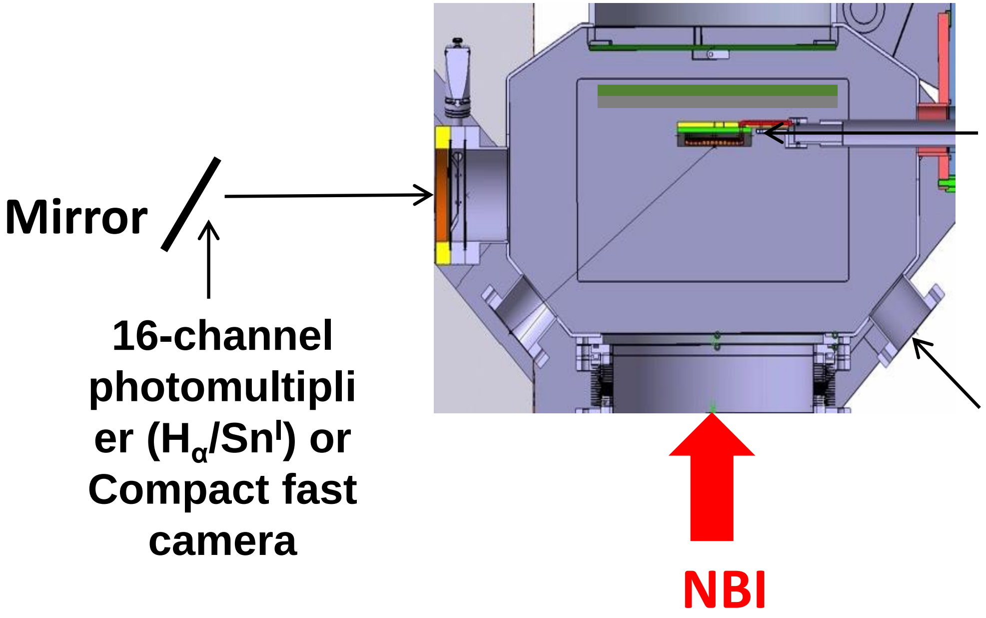
OLMAT HHF facility for LM PFC testing/development





Manipulator:
- 2 thermocouples
- Langmuir probe
- V float and I sat
- Rotatable target

3 of:
- 2 Pyrometers
- IR camera
- OES
- Fast camera

•Beam power load: 8±2 to 58±14 MW/m^2. Mixture of hydrogen neutrals and ions (33%).

•Primary energy of neutrals: 33 keV (21.7 keV for 3 component average), Flux :0.3-1.8·10^{22} m^{-2}s^{-1}.

Pulse duration up to 150 ms. FWHM ~ 11.7 cm

•Physics studies to characterize developed plasma cloud with Sn-CPS target in detached-like state. Ionization (electron and high-energy particle impact) of reflected hydrogen and evaporated/eroded tin behind plasma build-up and evolution. Investigate atomic processes between LM and energetic particles

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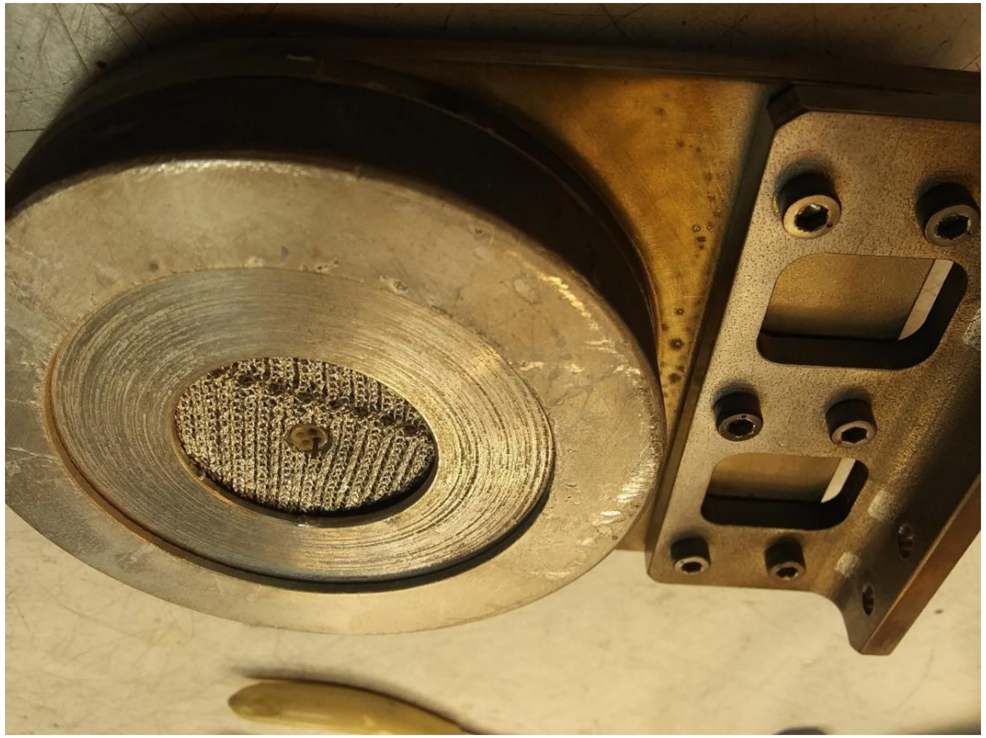
Exposition of Sn-CPS target with LP embedded

- W felt filled with Sn (provided by ENEA). d=37 mm Pore size 150-400 microns
- Characterization of plasma cloud at high temperature and power densities using embedded LP
- Operation with target tilted at 45º (protection of NBI against Sn vaporization). Comparison to TZM target
- 3 consecutive shots with 45 MW/m^2, 33% ion fraction and 100 ms length (304470-30472). Last shot at maximum achievable power (60 MW/m^2), same length and ion fraction (304473)



- **W tip (d=0,75 mm and L=3,45 mm in an Al_2O_3 tube (d=4 mm) embedded at Sn-W felt center**
- **Measurements taken within triangular I-V scans (-15 V, +15 V) at 3 kHz frequency**

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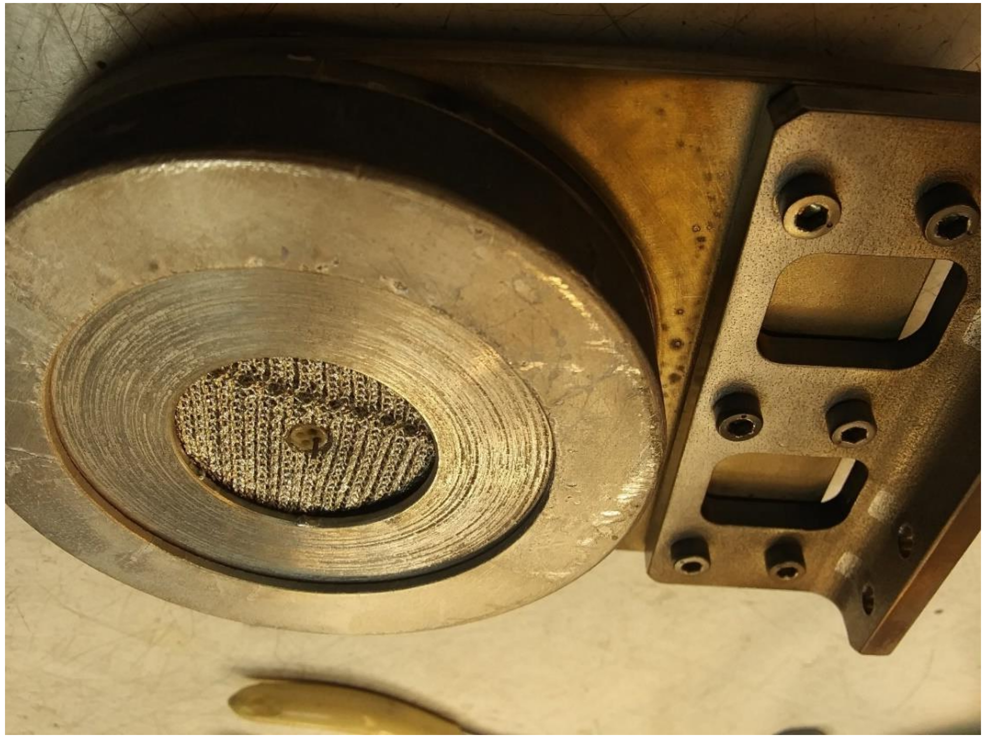

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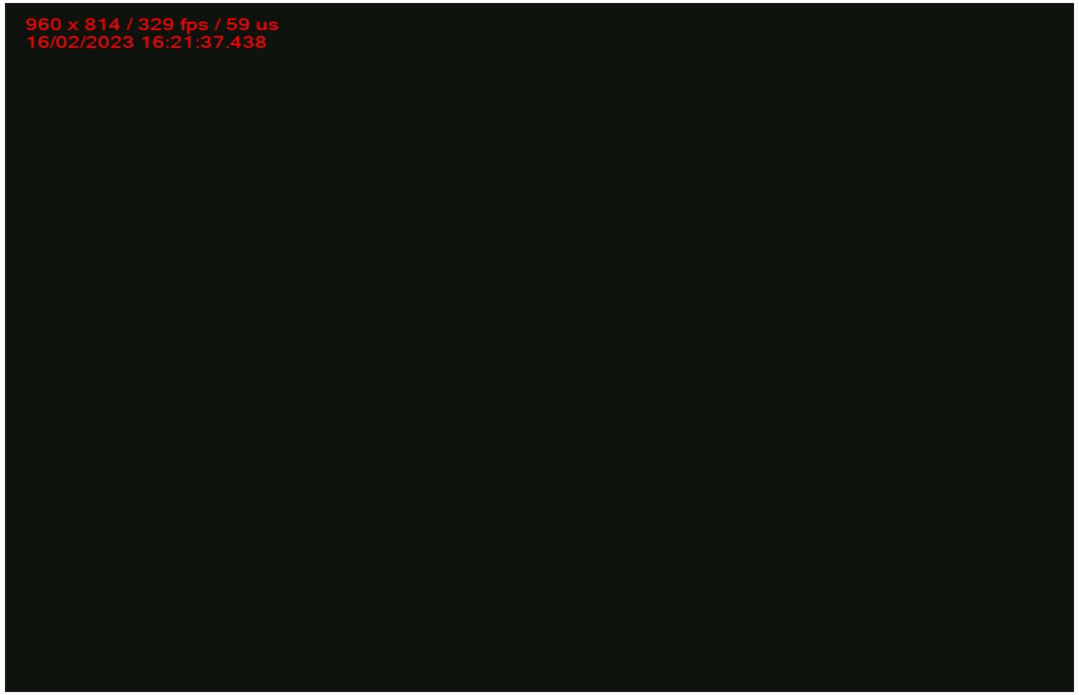
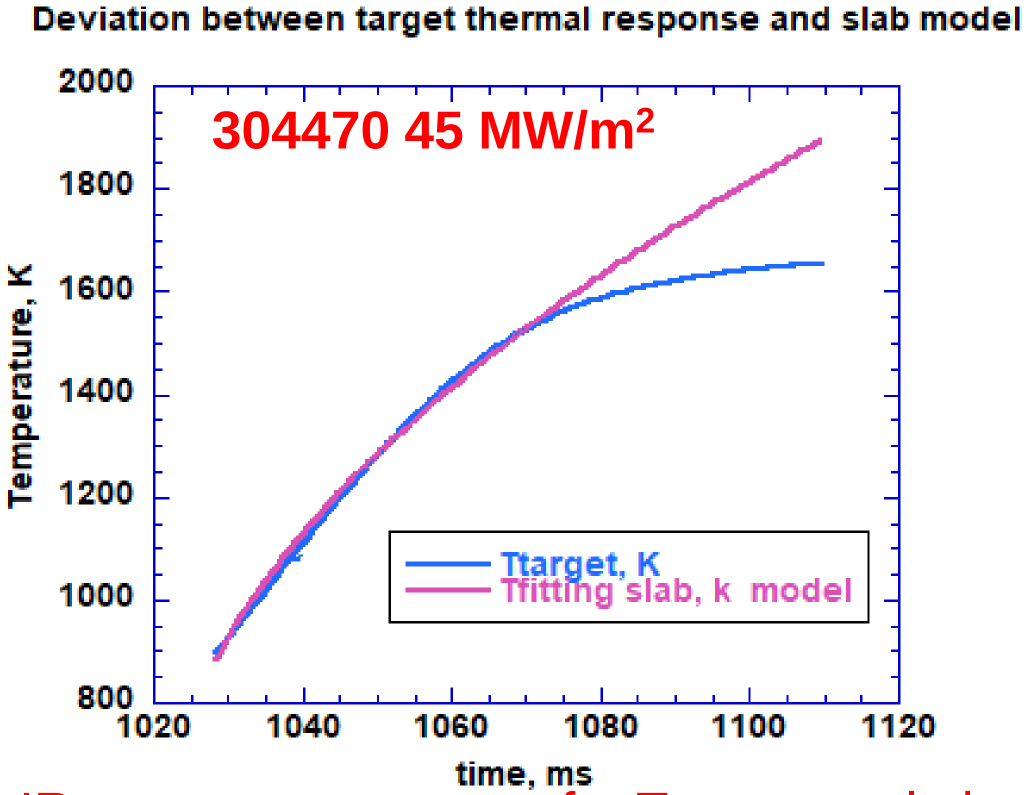
Exposition of Sn-CPS target with LP embedded

- In these shots, effects related to vapor shielding onset and associated radiative dissipation of incoming heat flux (T_{target} rise damped) were observed beyond 1600 K
- Analysis focused on 304470-72 (45 MW/m^2) and 304473 (60 MW/m^2).



Plasma cloud expansion within 9-12 ms phase
Stabilization after expansion 9-12 ms phase



IR pyrometry measure for Ttarget evolution

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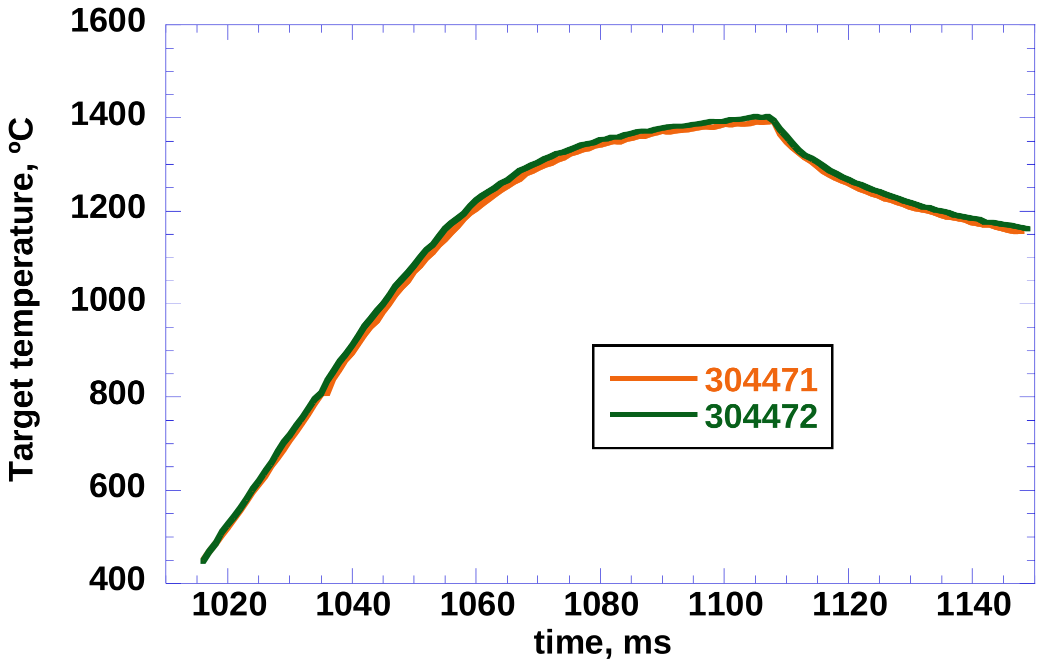
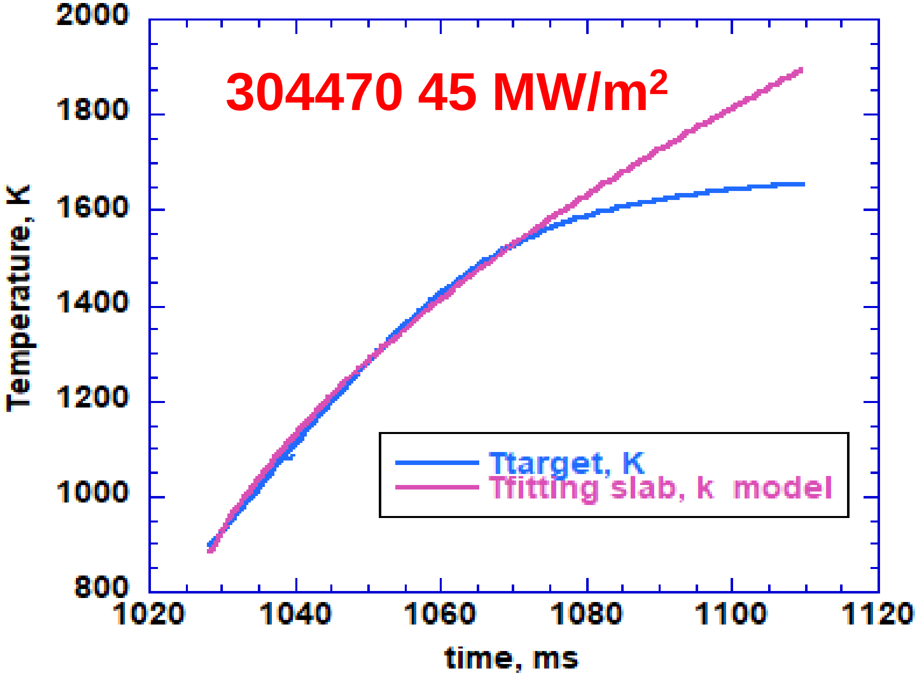
Exposition of Sn-CPS target with LP embedded

- 3 consecutive shots with 45 MW/m^2, 33% ion fraction and 100 ms length (304470-30472). Last shot at maximum achievable power (60 MW/m^2), same length and ion fraction (304473).
- Vapor shielding onset and associated radiative dissipation of incoming heat flux (T_{target} rise damped) were observed. Black body and vaporization losses <0.1 MW/m^2
- 304471-30472 Pulses at same initial T_{target} show a 100% reproducible thermal response
- Effect of window metallization on $T_{damping}$ beyond 1600 K is therefore negligible

Thermal response of Sn-W felt measured by pyrometry (45 MW/m^2 pulses)



Deviation between target thermal response and slab model



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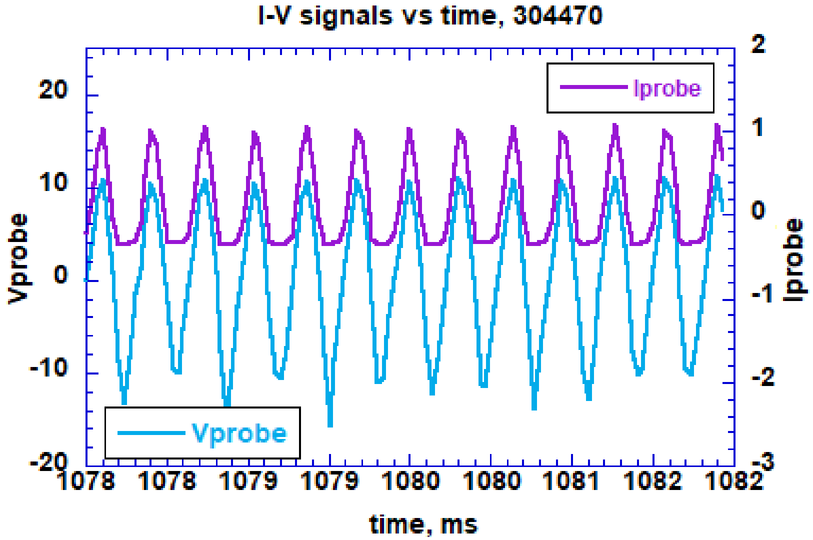
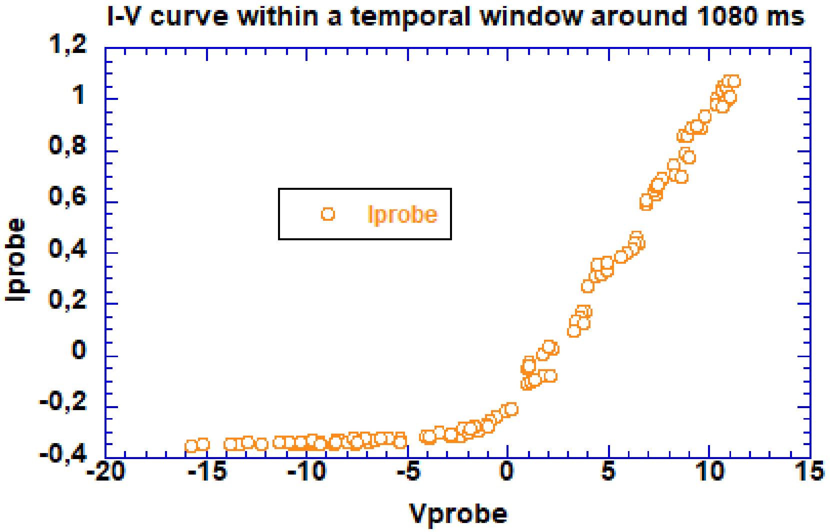
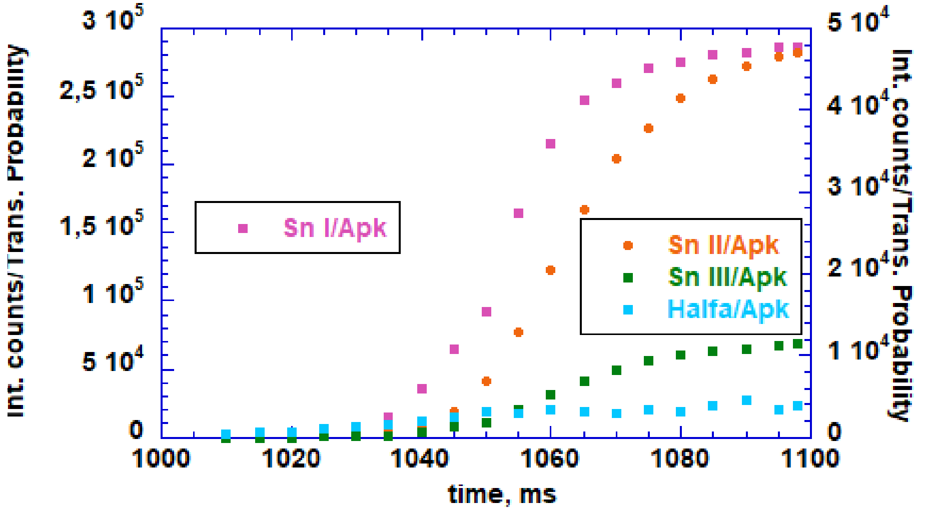
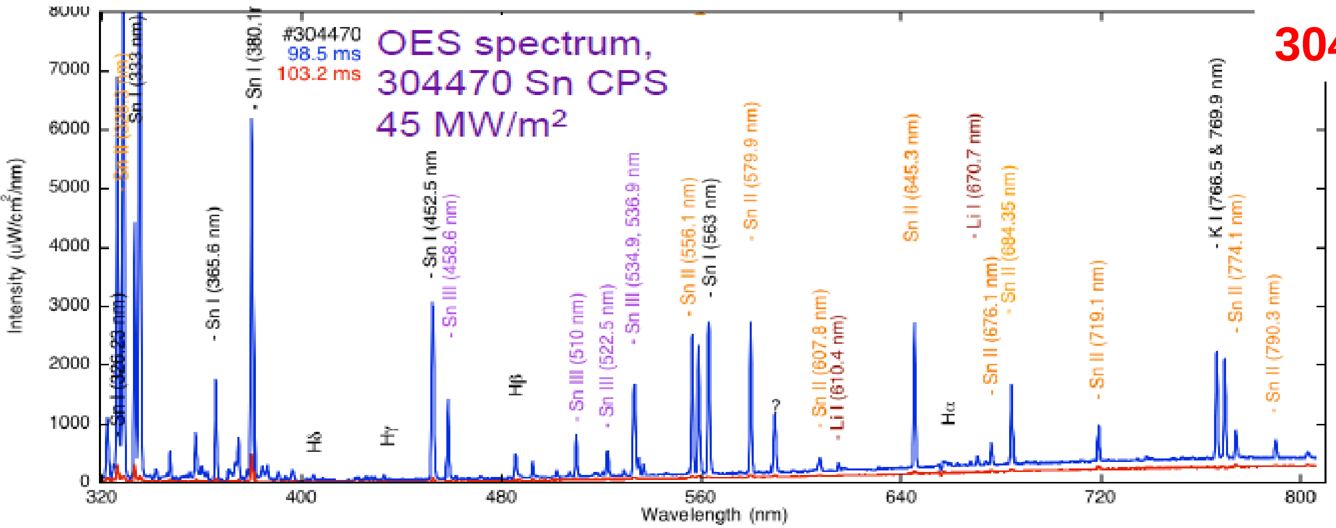
LP operation and characteristics

- Analysis averaging 25 I-V curves within 4 ms temporal window. Reasonable determination of I_{isat} unlike V_{plasma} and I_{esat}. Determination of electron temperature (T_e) from the I-V slope and density ($n_e \approx n_i$) from I_{isat}









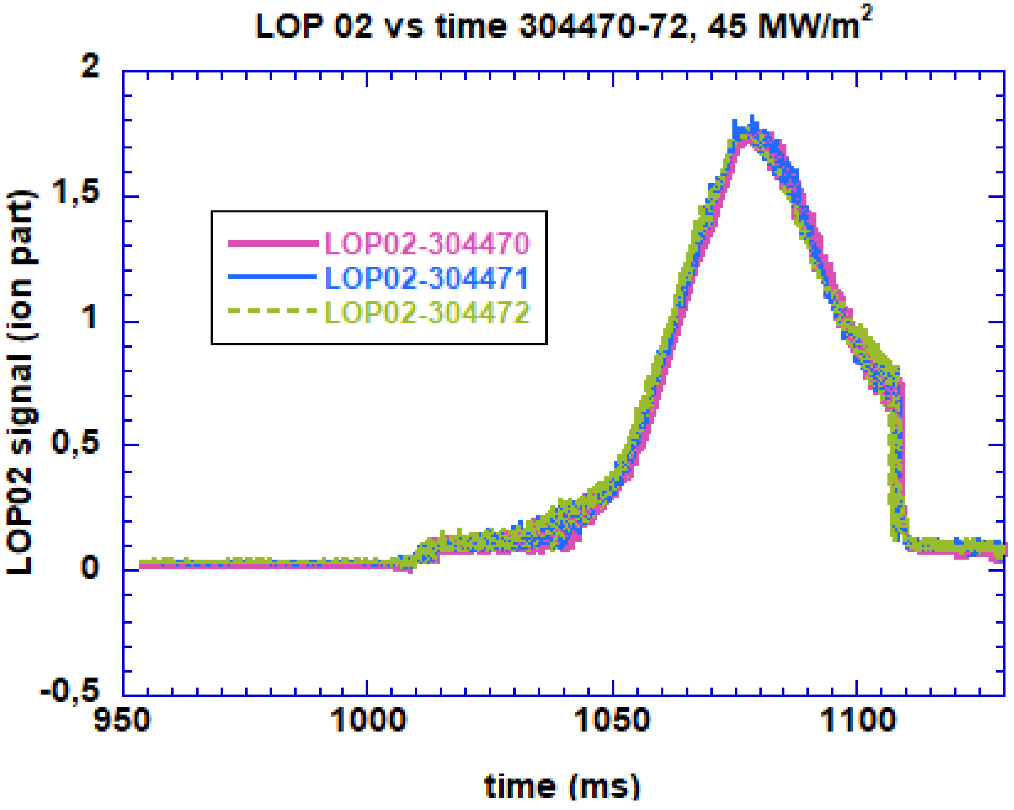
304470 Pulse with injected power density of 45 MW/m²

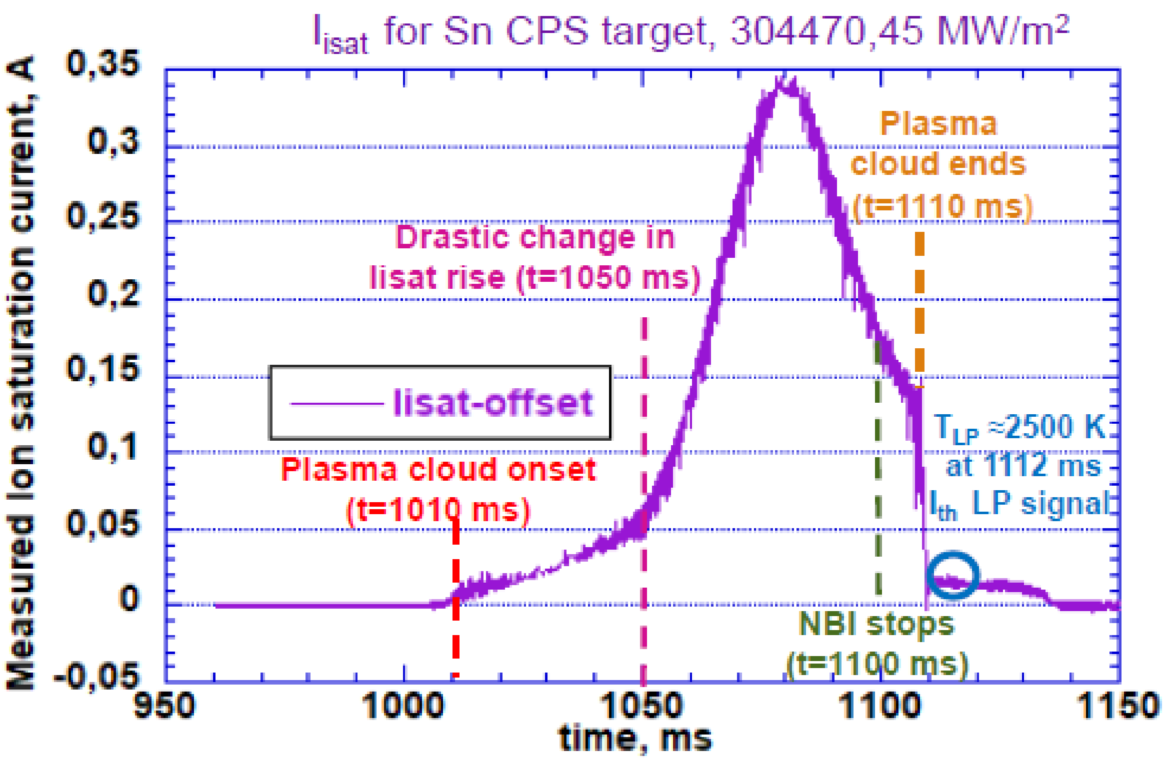
Sn I line at 452,5 nm , SnII line at 645,3 nm
Sn III 458,6 nm, Hα line at 656,3 nm
Sn II signal surpasses Hα for t>1050 ms.
Although H_α quenching is observed, the data suggests that Sn II population must clearly dominate beyond t=1060 ms

LP ion saturation current evolution

- Analysis averaging 25 I-V curves within 4 ms temporal window. Reasonable determination of I_{isat} unlike V_{plasma} and I_{esat}. Determination of Electron temperature (T_e) from the I-V slope and density ($n_e \approx n_i$) from I_{isat}

Pulse with injected power density of 45 MW/m²





Good reproducibility in I-V characteristics among same power discharges

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Method for LP interpretation and cloud dynamics analysis

1)Tin evaporation and deposition on LP tip increased collection area by a factor ≈1,7 (post-mortem measure)

2)Intense heating of LP tip and associated thermionic emission that disturbed I_{isat} measure:

$$I_{th} = 6.02 \cdot 10^5 \; A_p T^2 \cdot \exp\left(-\frac{e \cdot W_f}{k \cdot T}\right)$$

Estimation of LP tip temperature necessary to subtract it. IR fast camera measure were limited to low power shots (BaF2 window). Major emissivity uncertainties.

Sharp increase, immediately before Sn vaporization rise, attributed to thermionic after discounting adatom flux trend, giving a T_{LP} around 2700 K. Further rise is considered to be damped due to radiative plasma cloud keeping Ith approximately constant

3)Multi-species plasma (H and Sn) affecting the average mass of ions for density computations. Estimation of tin ion fraction in plasma (f_{Sn}) necessary to calculate it: $< m_i >= (1 - f_{Sn}) \cdot m_H + f_{Sn} \cdot m_{Sn}$

4) Presence of doubly ionized tin ions ($Sn^{III} \equiv Sn^{2+}$) affects ion saturation current and obtained density:

$$n_{i\,(Sn)} \propto I_{isat(Sn)} / (Z_{eff}); \quad Z_{eff,\,Sn} = 1 + \frac{\int Sn^{III}/A_{Sn^{III}}}{\int Sn^{II}/A_{Sn^{II}} + \int Sn^{III}/A_{Sn^{III}}}$$

A_{pk} being the transition probability

Effective contribution of Sn ions to I_{isat} subtracting TZM target and I_{th} values

$$I_{isat\,Sn\,eff} = \frac{I_{probe} - I_{isat\,TZM} - I_{th}}{Z_{eff\,Sn}} \qquad I_{isat\,net} = I_{isat\,TZM} + I_{isat\,Sn\,eff} \qquad f_{Sn} = \frac{I_{isat\,Sn\,eff}}{I_{isat\,net}}$$

Method for LP interpretation and cloud dynamics analysis

5) Doubly ionized tin ions also affect average ion velocity: $\mathbf{v_{th,i}} = \sqrt{\frac{8qkT_e}{\pi \cdot m_i}}$;

Global average charge of ions q (including H^+, Sn^+, Sn^{2+}): $\mathbf{q = 1 + f_{Sn} \cdot (Z_{eff\ Sn} - 1)}$

Introducing all these correction factors/considerations and assuming quasineutrality, electron density can be calculated as: $n_e \equiv n_i = \frac{4 \cdot I_{isat\ net} \cdot \sqrt{\pi \cdot <m_i>}}{\sqrt{q} \cdot e \cdot A_p \cdot \sqrt{8kT_e}}$

Comparison of computed densities to Sn vapor & NBI fluxes and pressures

Tin vapor and adatom fluxes (using equation given by Tabarés [1]) can be obtained with T_{target} evolution. Corresponding values of densities considering thermal Sn atoms at T_{target}. Comparison to NBI flux

$$\Gamma_{Sn\ adatom} = \gamma_{Sn\ ad} \cdot \Gamma_{H,NBI} = \frac{7.2 \cdot 10^5}{\sqrt{T + 1400}} \cdot \exp\left(\frac{-33000}{T + 1400}\right) \cdot \Gamma_{H,NBI}$$

$$\Gamma_{Sn\ vapor} = \frac{P_{vapor}}{\sqrt{2\pi m_{Sn} k T_{target}}} = \frac{10^{10.268 - 15332/T_{target}}}{\sqrt{2\pi m_{Sn} k T_{target}}}$$

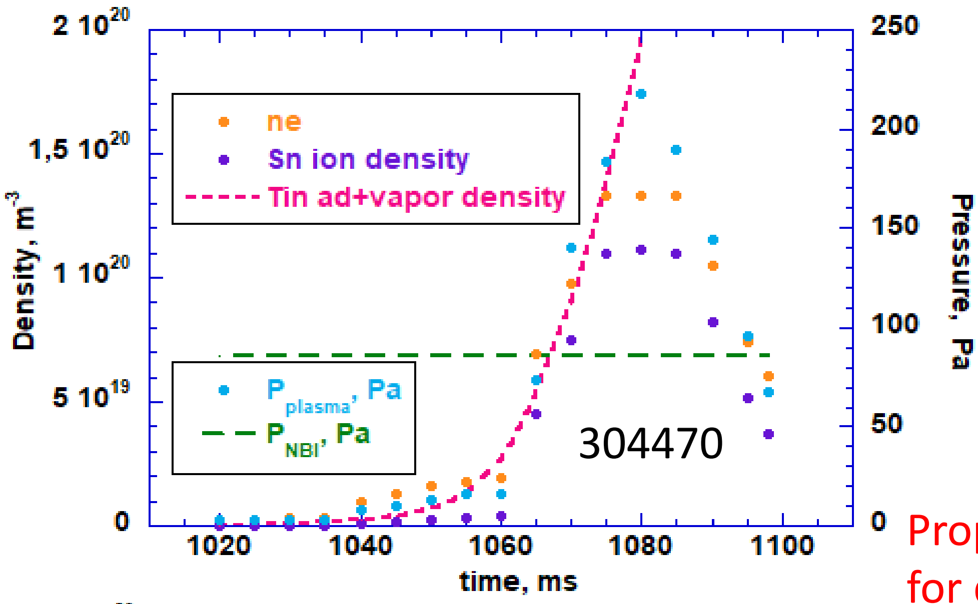
Once T_e, n_e and $n_{Sn\ ion}$ are obtained we can calculate corresponding plasma pressure and also compare it to the NBI pressure to infer expansion/compression dynamics

$$P_{NBI} = n_{NBI} k T_{NBI} = \frac{4\Gamma_{NBI}}{v_{th,NBI}} \cdot k \cdot T_{NBI}$$

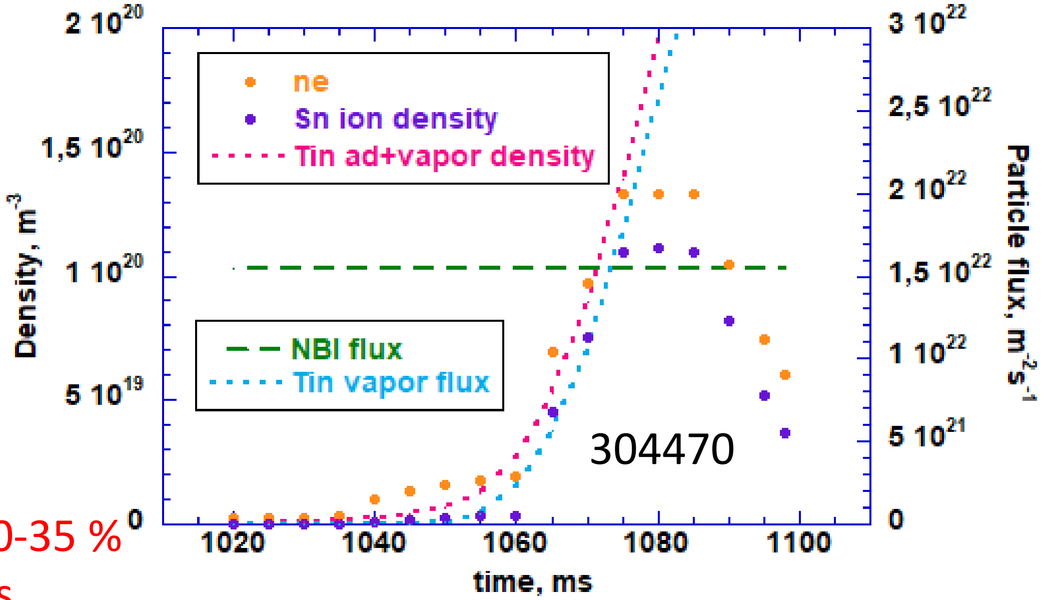
$$P_{plasma} = 2nkT$$

[1] F. L. Tabarés et al., 7th ISLA Symposium, Chubu University, Japan 2022

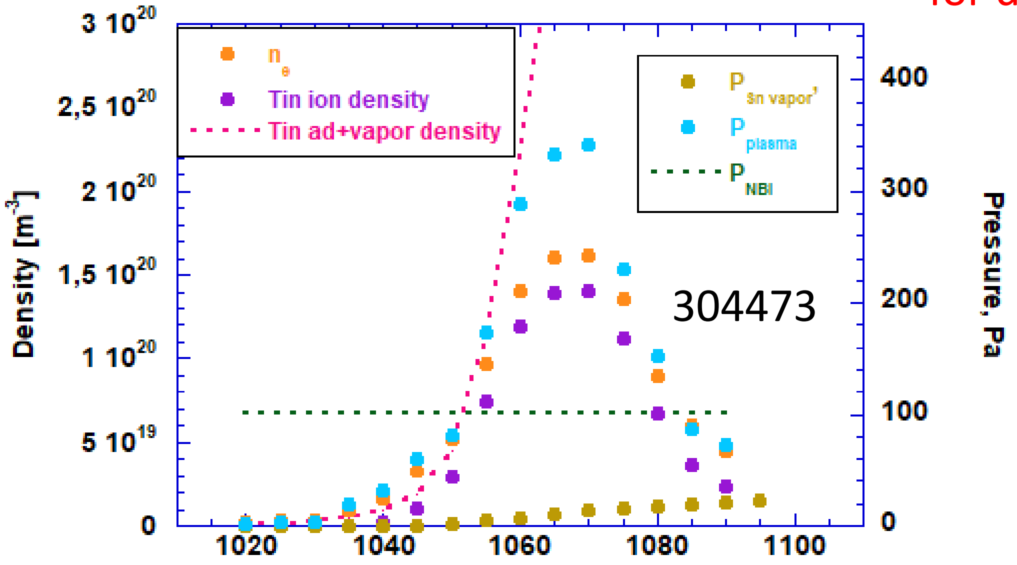
Density, pressure and flux evolution for 304470 and 304473



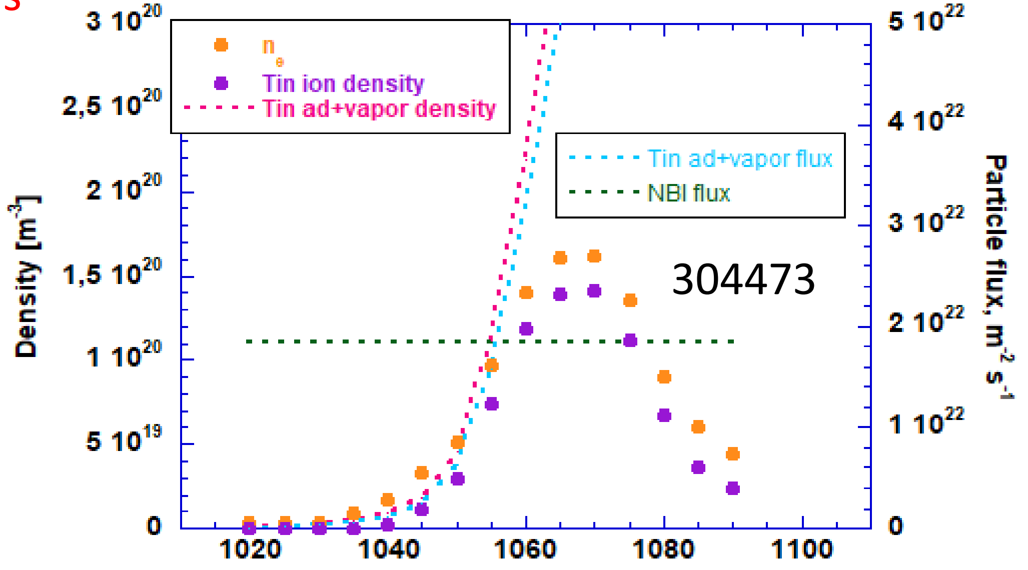
304470 45 MW/m^2
P_{plasma} and Sn vapor flux surpass NBI P and flux at 1065-1070 ms when T target rise starts to be damped.
Maximum densities around $1.3 \cdot 10^{20}$ m^{-3}



Propagated errors up to 30-35 % for densities and pressures

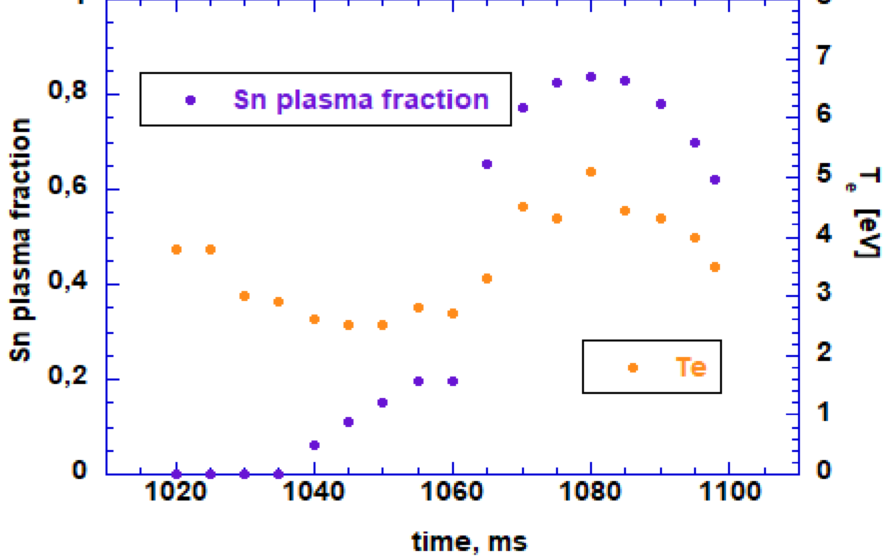


304473, 60 MW/m^2
P_{plasma} and Sn vapor flux surpass NBI P and flux at 1055 ms when T target rise starts to be damped
Maximum densities around $1.6 \cdot 10^{20}$ m^{-3}



Sn plasma fraction and Te evolution

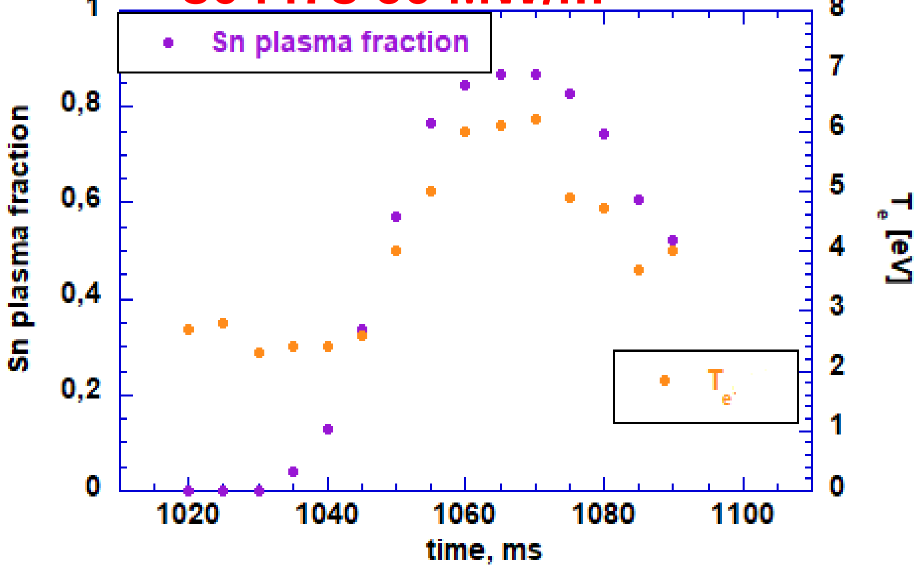
304470 45 MW/m^2



10% error T_e error bars
20-25% f_{Sn} error bars

Phase III appears faster as applied power density increases
Sn plasma fractions up to 85 %
T_e ranging from 2 to 6 eV where Sn ionization is more favoured than recombination [2]

304473 60 MW/m^2



-Phase I: (1020≤t<1040): H dominated, H reflection and subsequent ionization
-Phase II: (1040≤t≤1050-1060): H-Sn mixture (H reflection+ tin sputtering/adatom followed by ionization),
-Phase III: (1050-1055<t≤1070): Sn dominated plasma (vaporization) with increasing density produced by subsequent ionizations. Plasma expansion starts Ttarget rise starts damping (P_{plasma}>P_{NBI}). 10-15 ms phase agreeing with fast camera
-Phase IV: (1070<t≤1095 ms): Plasma expansion halts the rise of local density close to the LP tip and eventually causes it to decrease
-Phase V: (1095<t≤1100): Compression of plasma (P_{plasma}<P_{NBI}) and shot end followed by plasma decay

Detached-like state at lower T_{target} when compared to Magnum PSI device [2](1800-2000 K)
role of radiative processes from high energy particle impact with Sn species

[2] G. G. van Eden et al., Nat. Commun. 8, (2017) 192

Conclusions and future works

- Tin plasma clouds are characterized locally by single LP embedded within the LM PFC. Basic plasma parameters that will help in the comprehension/validation of Sn vapor shielding and radiative processes induced by high-energy particle impact
- A method has been developed to infer density values within a complex plasma characterized by: a multi-species (H, Sn), multi-charged ion (H^+, Sn^+, Sn^{2+}) environment this being affected also by thermionic emission
- Local densities between $5 \cdot 10^{18}$ and $1.6 \cdot 10^{20}$ m^{-3} have been computed, transitioning from an almost pure H plasma (created by particle beam reflection and ionization) to a plasma considerably enriched with Sn ions (f_{Sn} up to 85%) with T_e between 2 and 6 eV
- Deduced expansion of the plasma cloud against the NBI beam ($P_{plasma\ cloud}$>P_{NBI}) reasonably agrees with fast-frame camera observations (location in the shot and phase duration)
- Plasma phase characterized by Sn vapor fluxes larger than NBI ones, where vapor shielding/impurity radiation effects (at T_{target} around 1600 K) are observed (T_{target} rise damped) in detached-like state
- Heat flux dissipation effects observed at lower T_{target} when compared to Magnum linear plasma device results (~2000 K)
- Role of radiative processes, driven by the interaction of high-energy H particles with vaporized and plasma Sn species . Work is underway with thicker LPs to minimize thermionic emission effect

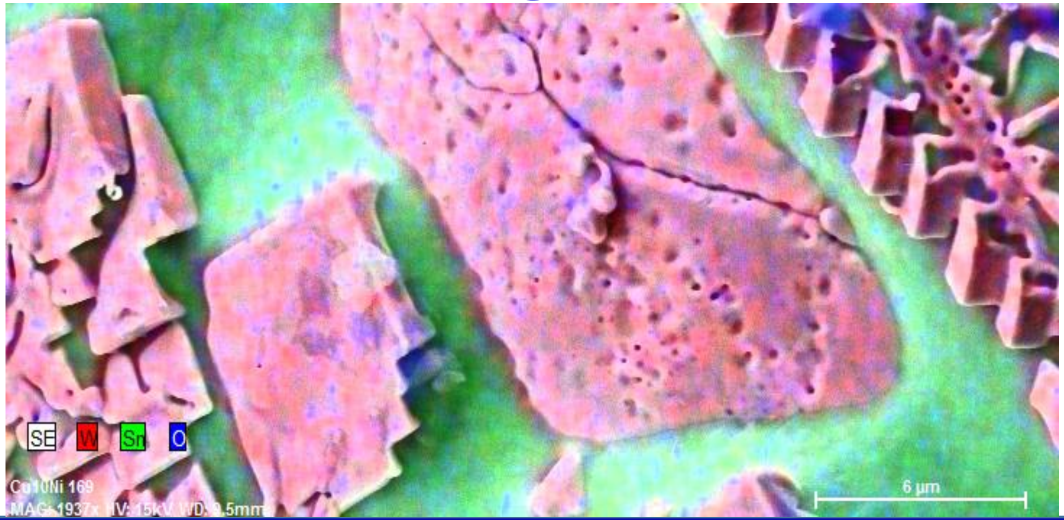
THANKS FOR THE ATTENTION

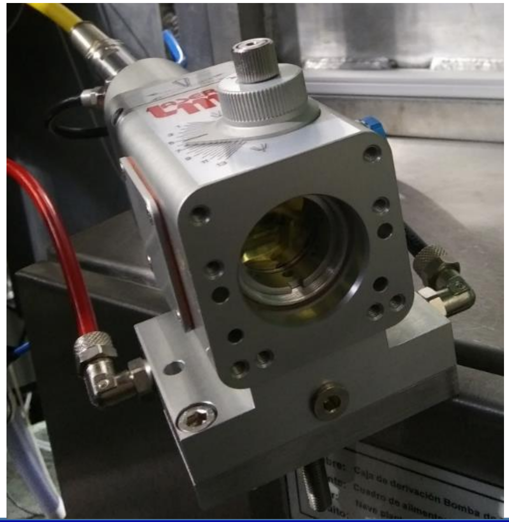
The facility is open to international collaboration with both public and private partners working with LMs worldwide

High-power CW Laser for disruption/ELM mimicking commissioned

Technology and pure material science research

alfonso.decastro@ciemat.es



EXTRA SLIDES

Outline

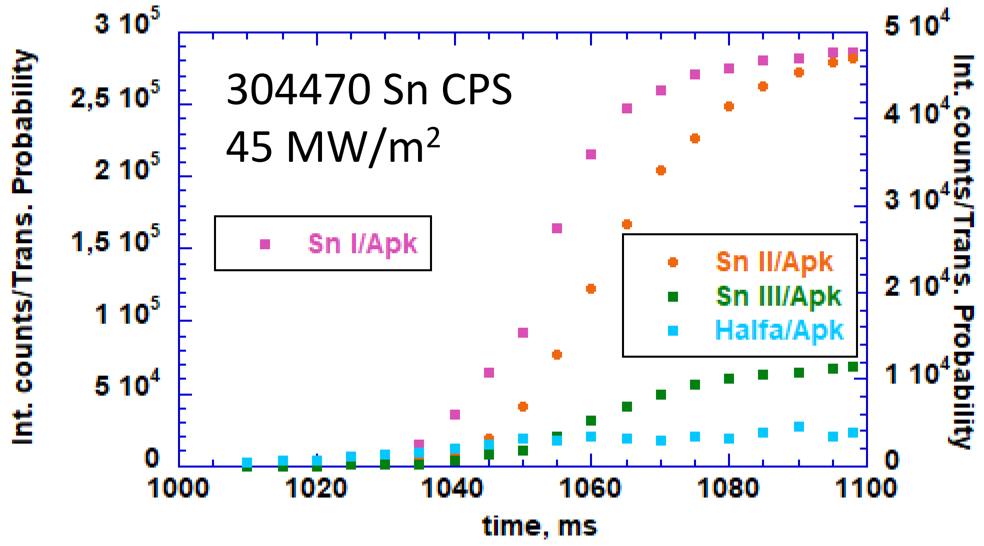
- OLMAT as a HHF facility for LM PFC testing/development
- Exposition of Sn-CPS target with LP embedded
- LP operation, characteristics and evolution. OES measures
- Method for LP interpretation and cloud dynamics analysis
- Results for density, Te, fluxes and Sn plasma fraction evolution
- Conclusions and future works

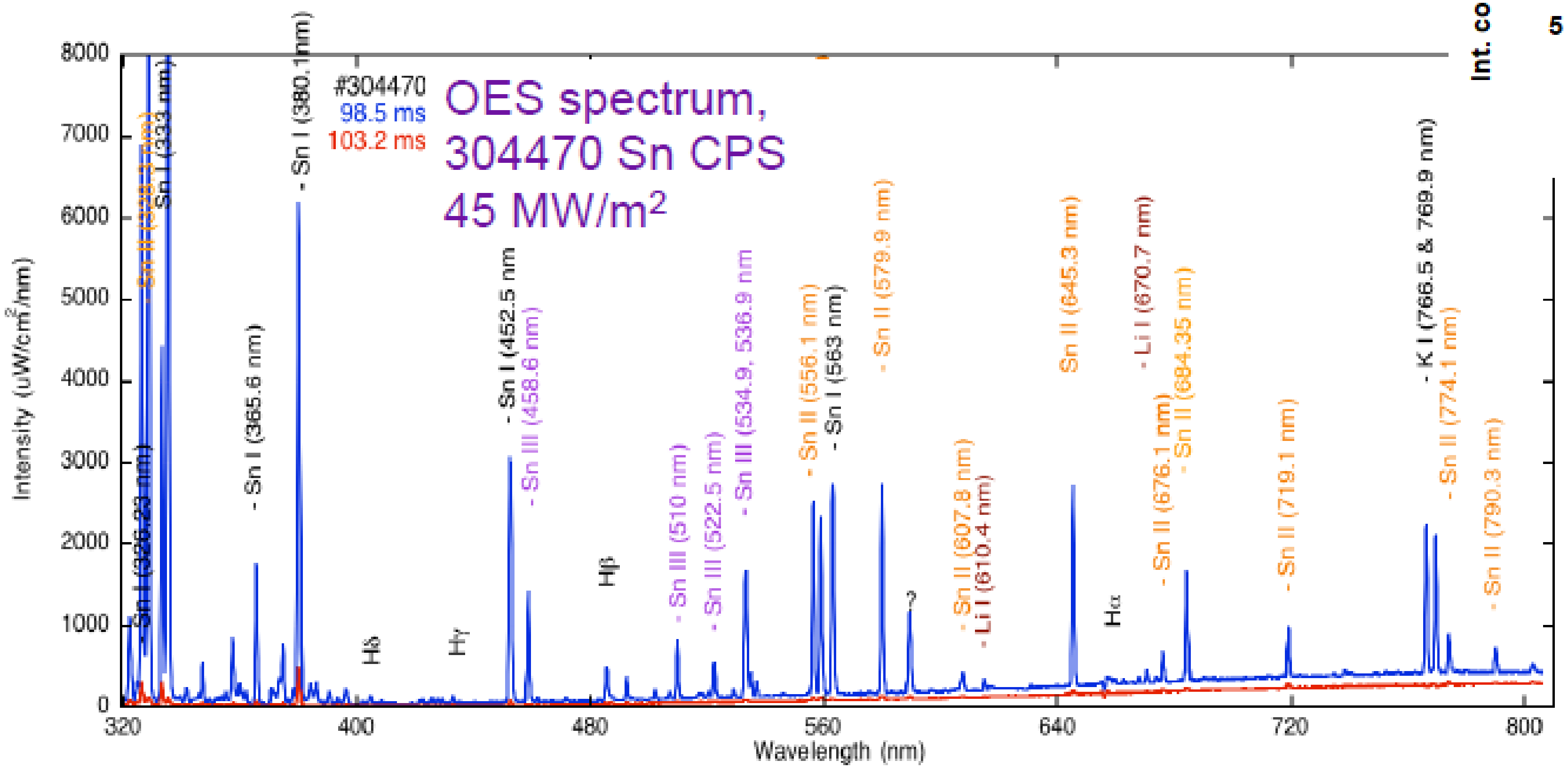
OES measurements for qualitative plasma characterization

Majority presence of tin ions from t>1050 ms.

Tin ions in singly and doubly ionized states (Sn II,Sn III lines)

Black body radiation corroborates T_{target}





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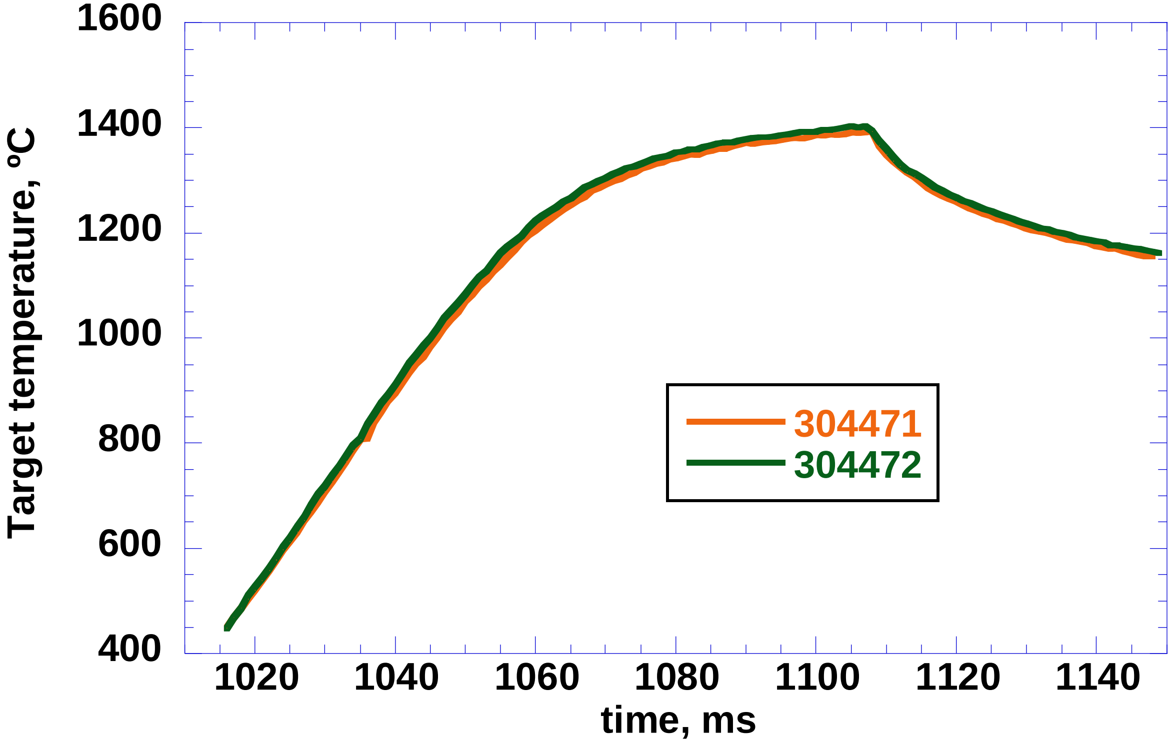
February 2023 Experimental campaign (22/2/2023)

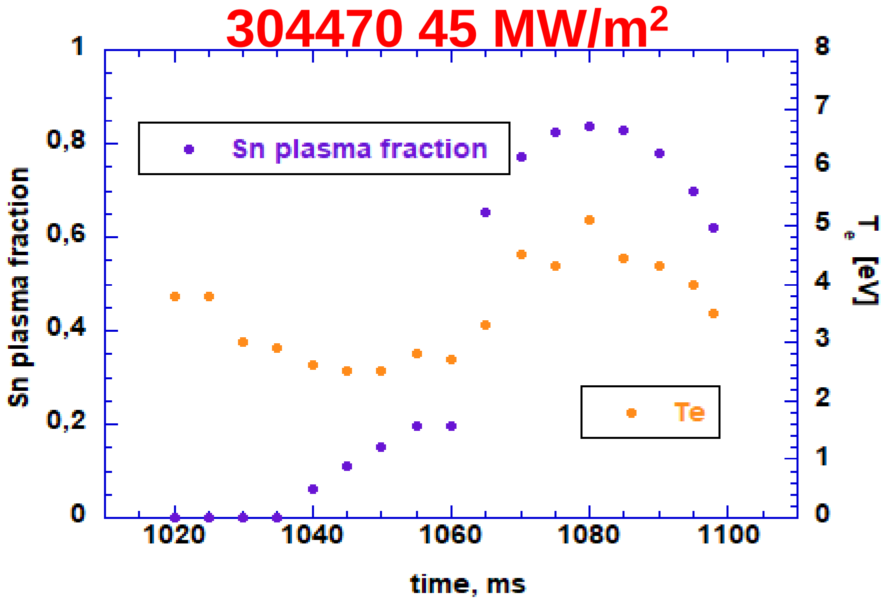
- W felt filled with Sn (provided by ENEA) Pore size 150 microns
- Operation with target tilted 45º (protection of NBI against massive Sn vaporization)
- Successful operation and LP measurements even at largest power densities

Thermal response of Sn-W felt measured by pyrometry (45 MW/m^2 pulses)

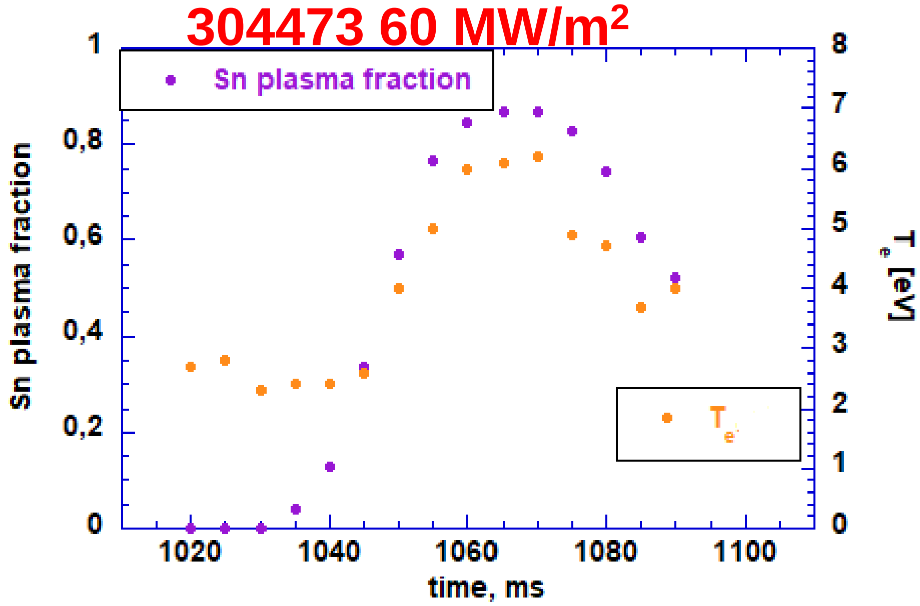


- Pulse of 100 ms duration (starting at t= 1000 ms)
- Pulses at same initial Ttarget show a 100% reproducible thermal response
- Effect of window metallization on $T_{damping}$ beyond 1200ºC (Vapor shielding onset) is therefore negligible

Sn plasma fraction and Te evolution



Phase III appears faster as applied power density increases
Sn plasma fractions up to 85 %
T_e ranging from 2 to 6 eV where Sn ionization is more favoured than recombination [2]



-Phase I: (1020≤t<1040: H dominated, H reflection and subsequent ionization
-Phase II: (1040≤t≤1050-1060): H-Sn mixture (H reflection+ tin sputtering/adatom followed by ionization),
-Phase III: (1050-1055<t≤1070): Sn dominated plasma (vaporization) with increasing density produced by subsequent ionizations. Plasma expansion starts when damping of the target temperature rise also begins (P_{plasma}>P_{NBI})
-Phase IV: (1070<t≤1095 ms): Plasma expansion halts the rise of local density close to the LP tip and eventually causes it to decrease
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10% error T_e error bars (fitting and I_{probe} measure)

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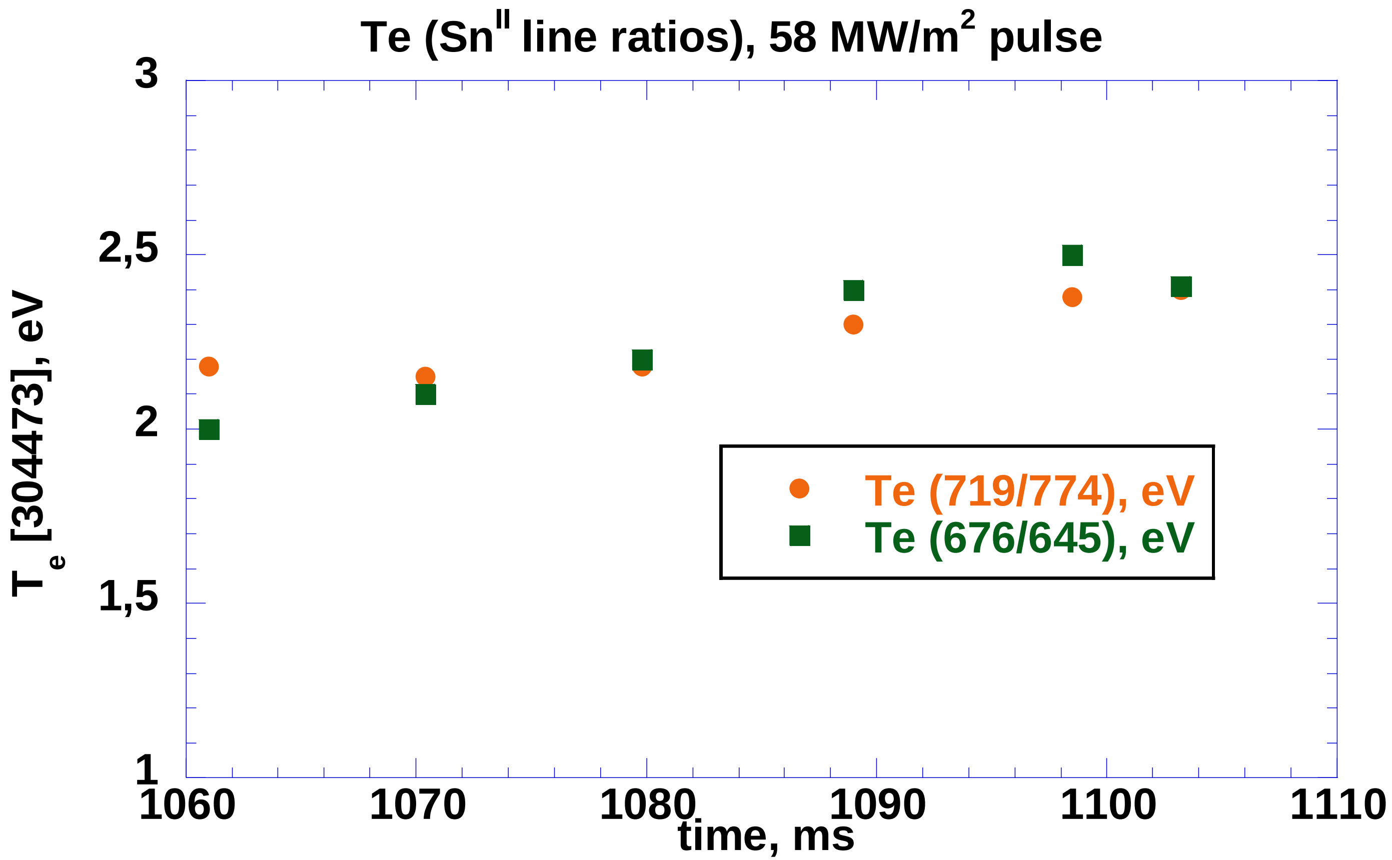
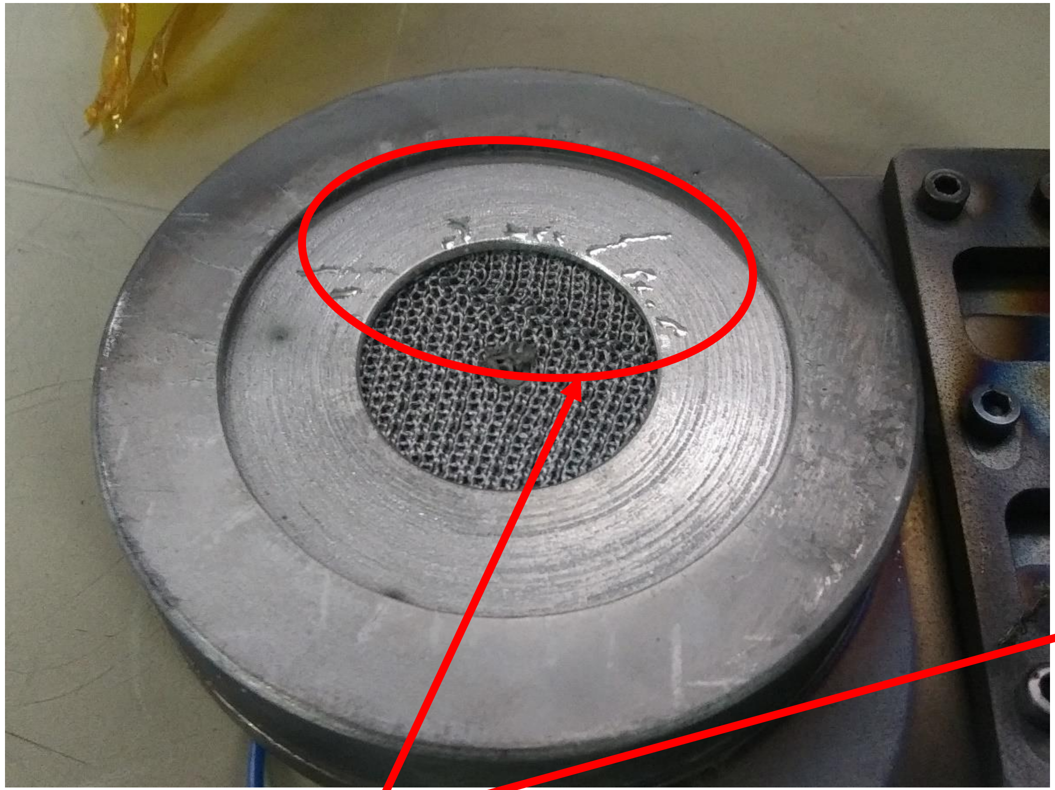


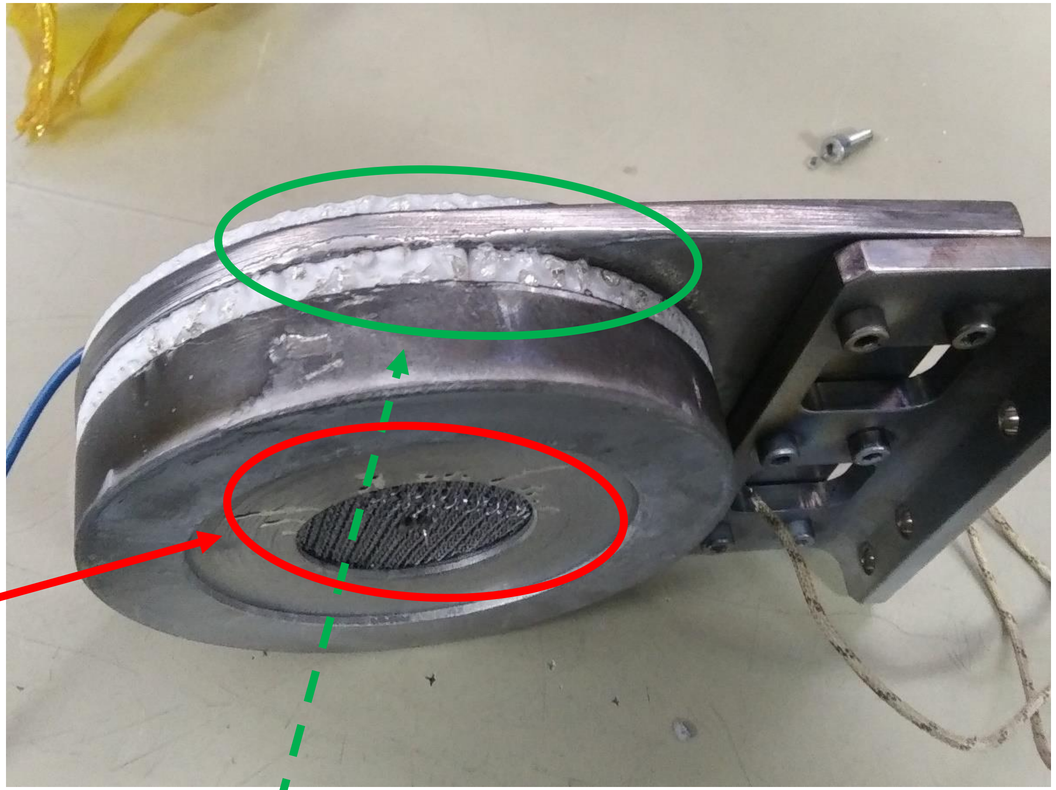
Pulse with injected power density of 58 MW/m^2 and 100 ms (not equivalent to previous ones)

- **Sn II line ratios as alternative measurement for Te. First estimations**
- Balmer lines ratio analysis inconsistent (plasma dominated by Sn)
- Complete analyses (LP and Sn^{II} OES) and characterization/quantification of vapor shielding/radiation effects are ongoing

February 2023 Experimental campaign

- W felt filled with Sn (provided by ENEA) d=37 mm. Pore size 150 microns
- Characterization of plasma plume/cloud at high temperature and power densities by embedded LP
- Operation with target tilted 45º (protection of NBI against massive Sn vaporization)
- Successful operation and measurements even at largest power densities





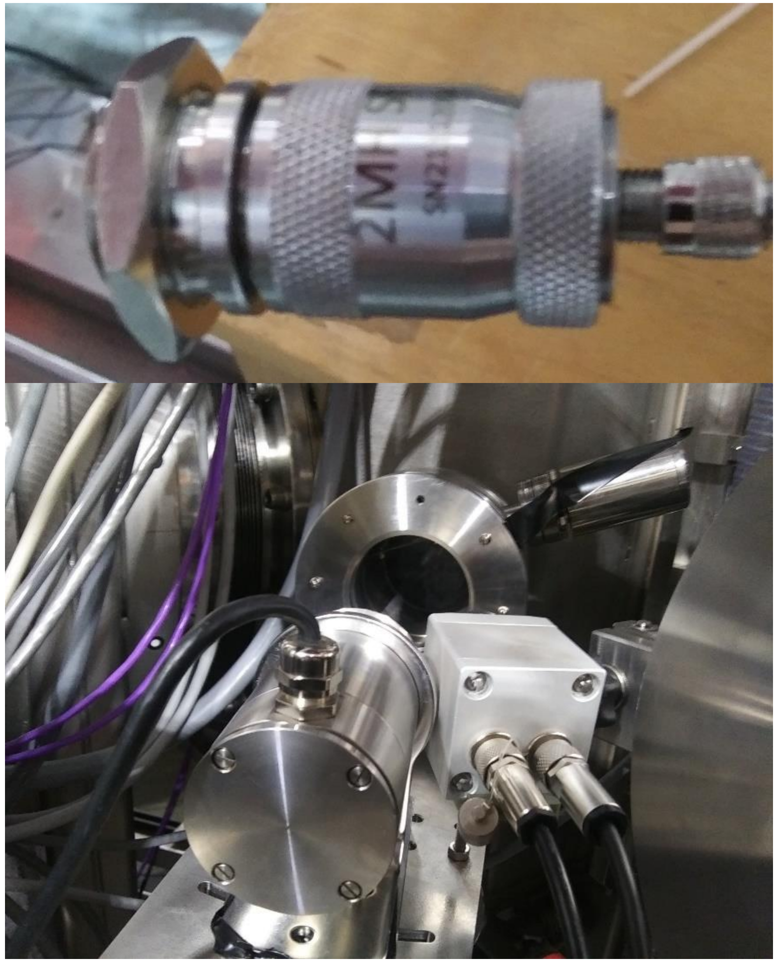
- Signs of **tin accumulation** on edge closer to beam. Eroded/vaporized/ejected contributions?
- Erosion on exposed Macor at **target backside tilted to the beam** and BN (probe tube)

OLMAT as a HHF facility for LM PFC testing and development

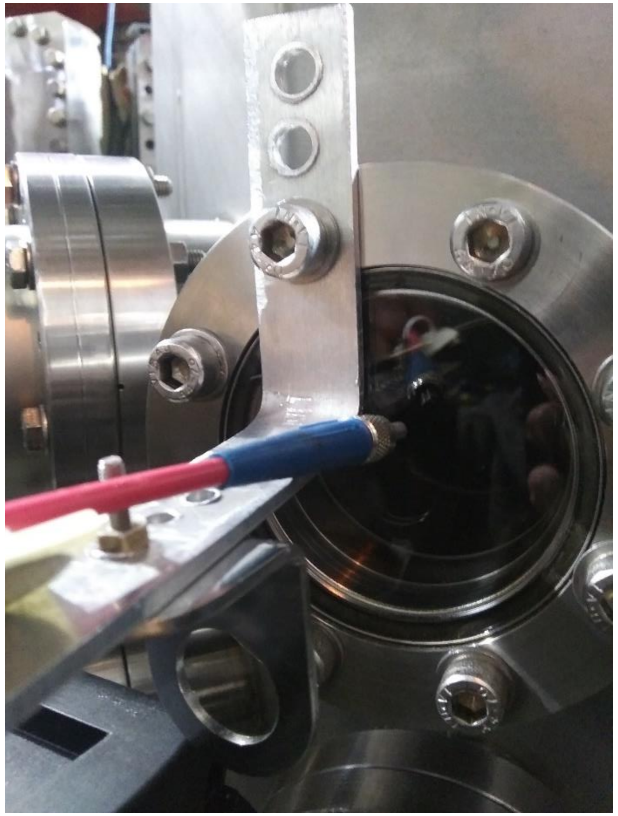
16-channel Sn, Hα array

Compact fast-frame camera

Diagnostics



Pyrometers and IR camera



CMOS-based spectrometer
236-812 nm

EXTRA SLIDES

Summary and future works

- **Experimental campaign will continue in March with additional testing of AUG mockups**
- **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/dry-out**
- **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**

Basically to all of you

Thanks for the attention!

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