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Studies of Thermal Sputtering and Vapor Shielding of Sn in the OLMAT HHF Facility

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OUTLOOK



- Motivation
- Plasma Characterization.
- Thermal Sputtering of Sn
- Vapor Shielding effects
- Conclusions.

Why these studies



- Liquid Metals are a reasonable alternative to solid targets for a fusion reactor (*lack of permanent damage, in situ refilling, tritium extraction, etc...*)
- They have some peculiarities *wrt* impurity generation:
 - 1) Droplet ejection (- -) **CPS solution?**
 - 2) Thermal (enhanced) Sputtering (-)
 - 3) Vapor Shielding effects (+)+missing AM data for diagnostics/modeling: CRP launched by IAEA
- **Studies in OLMAT (de Castro presentation):**
 - 1) Optimization of CPS geometry (Oyarzabal presentation)
 - 2) Thermal sputtering
 - 3) Vapor Shielding
 - 4) Generation of a AM data base for LM's (?)

Contribution of Sn vapor shielding studies to the IAEA CRP on VS



- Sn outstands as first LM candidate for DEMO divertor (recently tested in AUG)
- Compared to Li, Sn is far less studied (AM database)
- Thermal sputtering may be the main contributor to impurity fluxes in LM-based divertor targets
- In cold divertors, high Z Impurities are mostly generated by keV ion sputtering during ELMS (JET, AUG, 20keV in ITER?..)
- Vapor shielding effect for Sn seen in Pilot PSI at 2000K
- OLMAT offers reproducible conditions at high powers (up to 60MW/m^2) Suitable for AM studies thanks to local plasma characterization.

The OLMAT HHF Facility

OLMAT : Optimization of Liquid Metal Advanced Targets

Alternate use of TJ-II Neutral Beam Injectors for material irradiation in a test bed and for plasma heating in a magnetized fusion device.

Project deployed in three phases

Phase 1) NBI exposure of LM prototypes. Comparative studies (<150ms pulses, no ELMs)

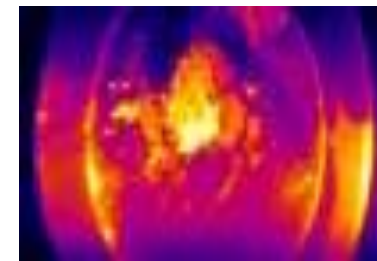
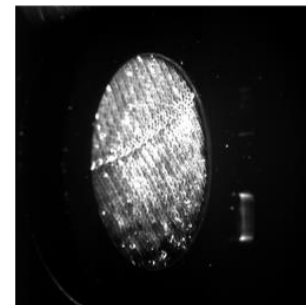
✓ **Phase 2) Addition of ELM-like loads (Laser pulses)**

Phase 3) Long NBI pulse (up to 5 s)+ ELMs

$E_{\text{beam}} < 32\text{kV}$ (3 components, $E_0, 1/2$ and $1/3$)
 $W < 705\text{ kW}$ ($60\text{MW}/\text{m}^2$) $\Gamma < 1,5 \cdot 10^{22}\text{ m}^{-2} \cdot \text{s}^{-1}$

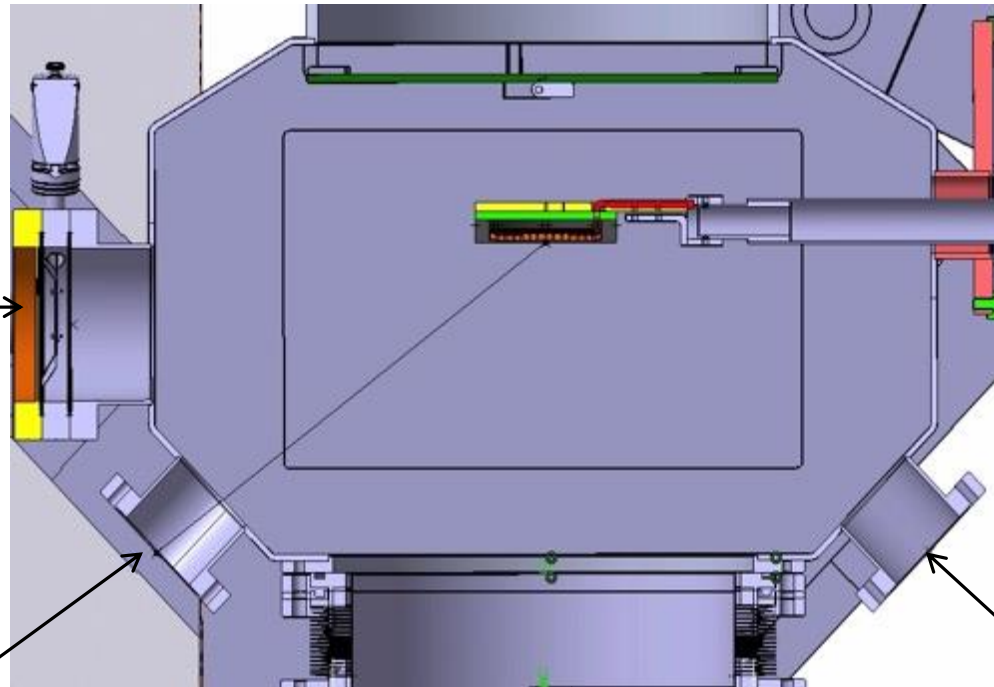
Operation start-up: April 2021

- Liquid Sn and several CPS structures tested
- Also used for ITER amour material tests (TZM, W).



Diagnosics

TJII



Mirror

16-channel photomultiplier array
Sn, Halfa filter

Fast camera (new)
Sn, Halfa filter

+ Laser 9kW pulsed

NBI

IR camera

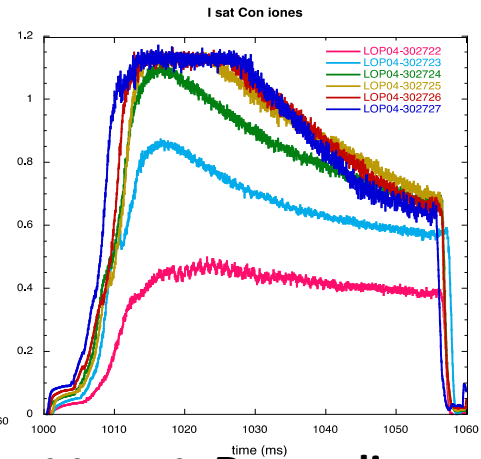
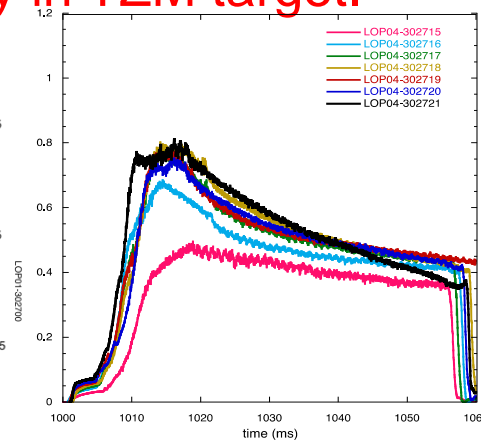
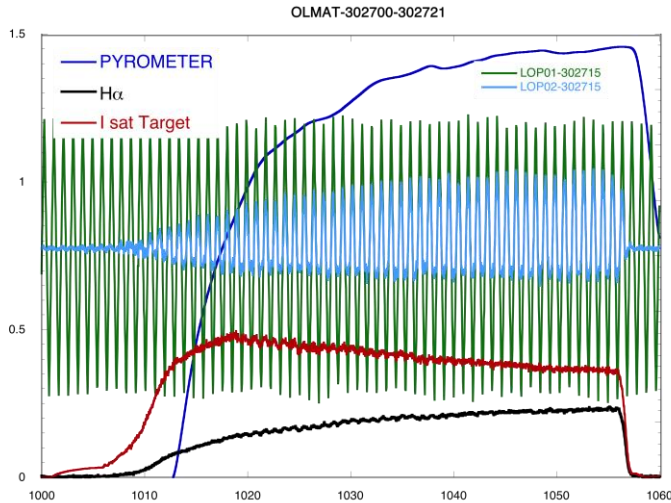
Thermocouples
Vfloating and Isat.
+Lang. Probes in TZM!!

Pyrometers
CMOS-based spectrometer
Spectra from 236 to 812 nm.

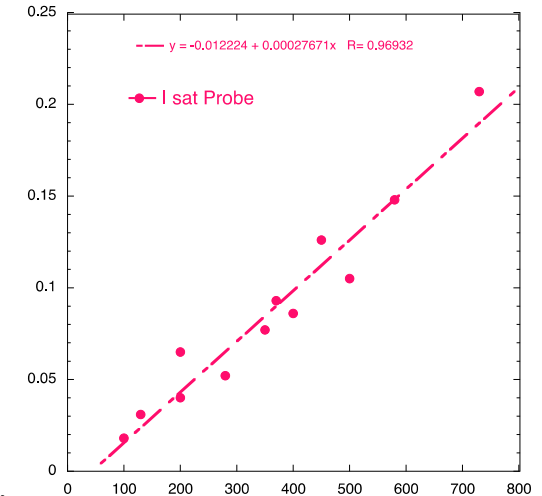
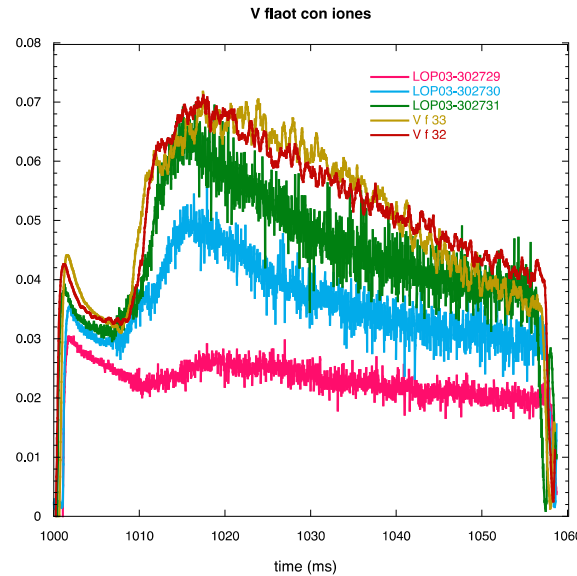
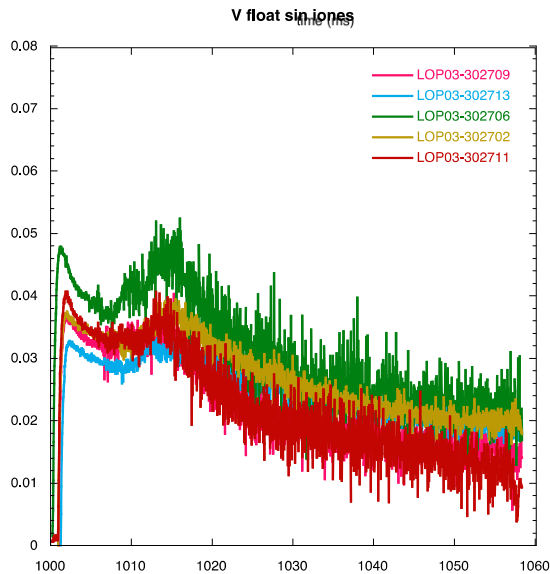
Electric Characteristics in TZM target



- Preliminary results. **Only in TZM target.**



I sat, V float target: Depending on power and ion contribution



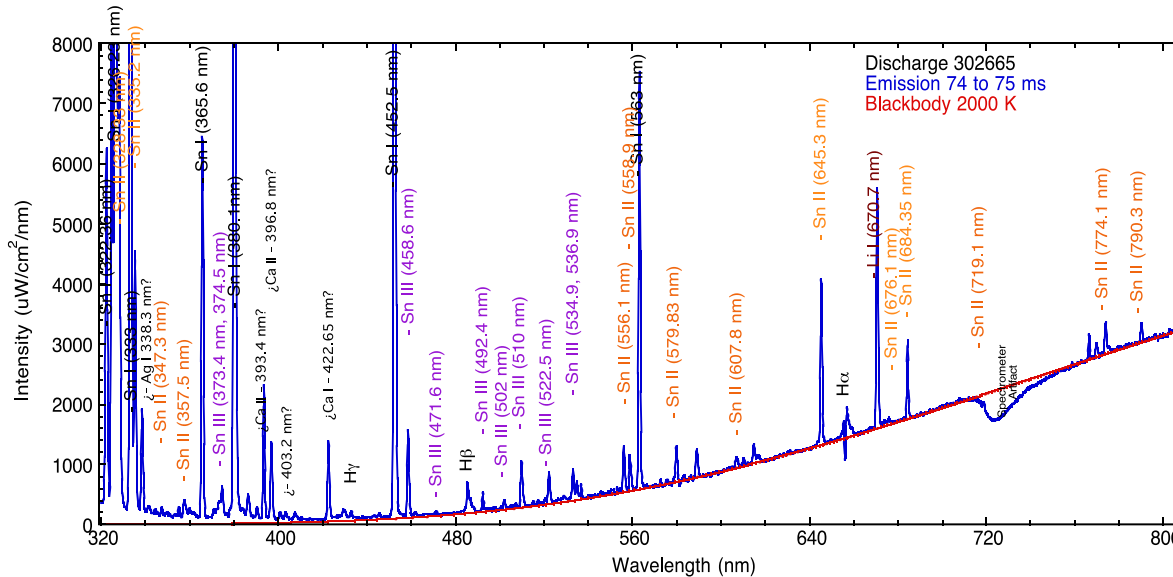
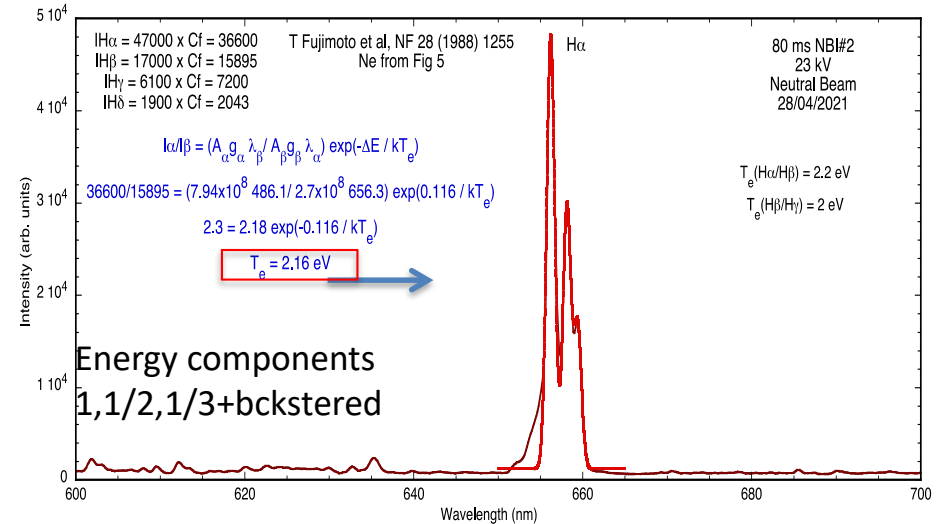
But: I_{sat} probe \sim power

Plasma parameters. Spectroscopy



A plasma is generated by the interaction of High Energy H atoms and target.

- How? : $H_{hot} + H_2 \rightarrow H_2^{++} + e^-$, SEE by high E_{ptcl} impact on metals >1, others?.
- Clear dependence of plasma parameters on target material (work function, recycling?).



- SnI, II and III lines detected
- Weak H emission lines
- Ratio SnI/SnII, $T_e=1.5$ eV
- Black Body spectrum: T_{sample}

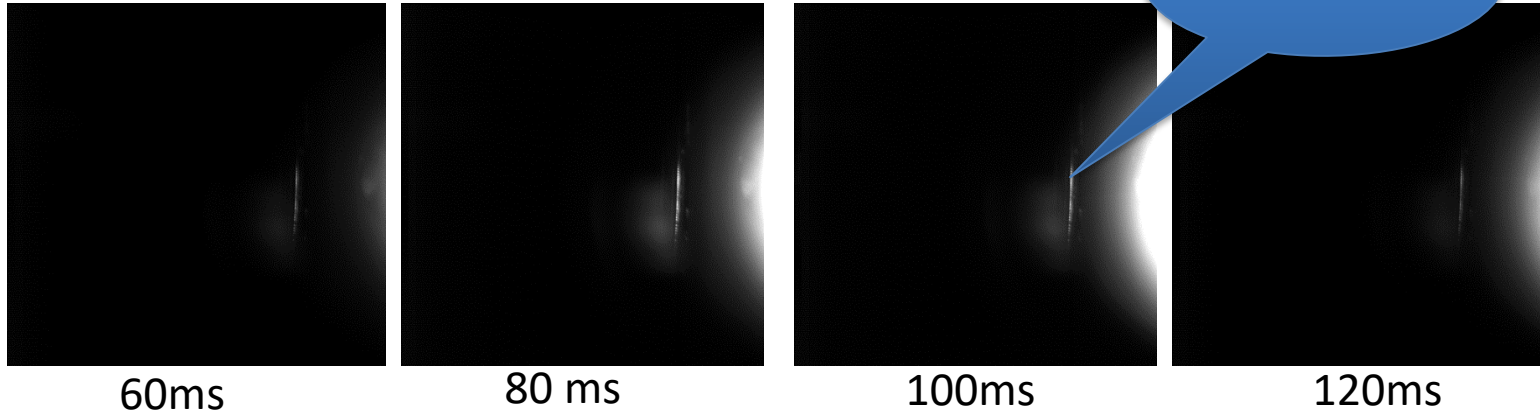
Generation of a pure Sn plasma?

Emission profiles

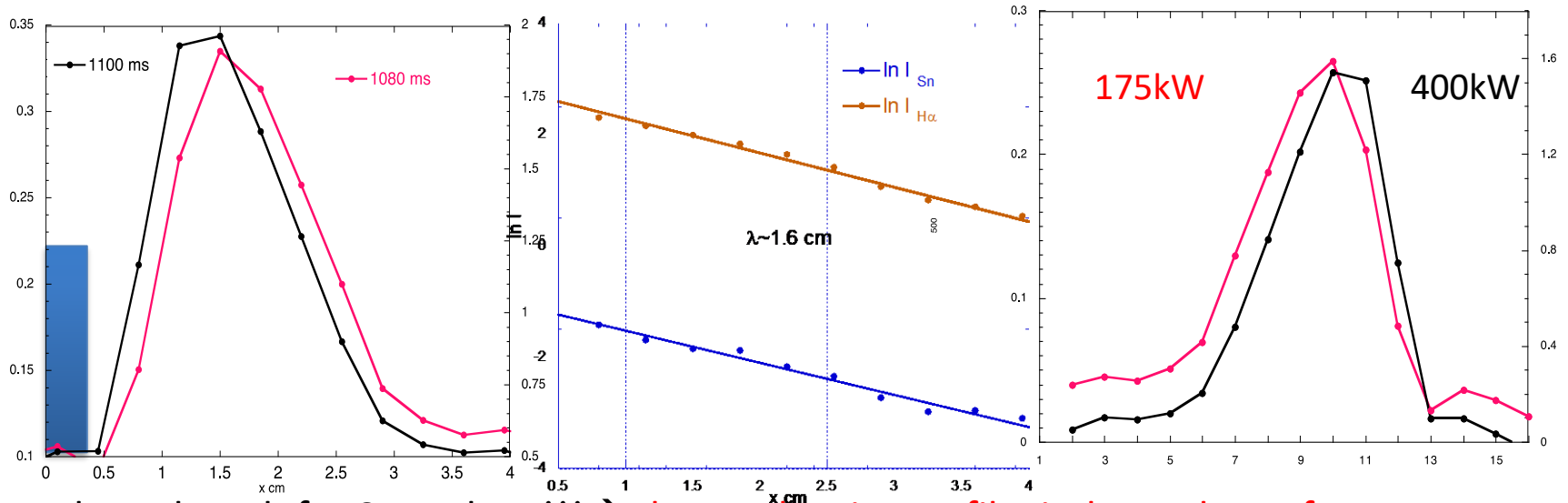


Fast camera from perpendicular LOS. Sn filter @ 452 nm.

Reflexion?



PM Array: 1ch=0.35cm



Same decay length for Sn and H α !!! \rightarrow Plasma density profile, independent of Power

Studies of thermal sputtering of Sn



T Abrams, FED 2014

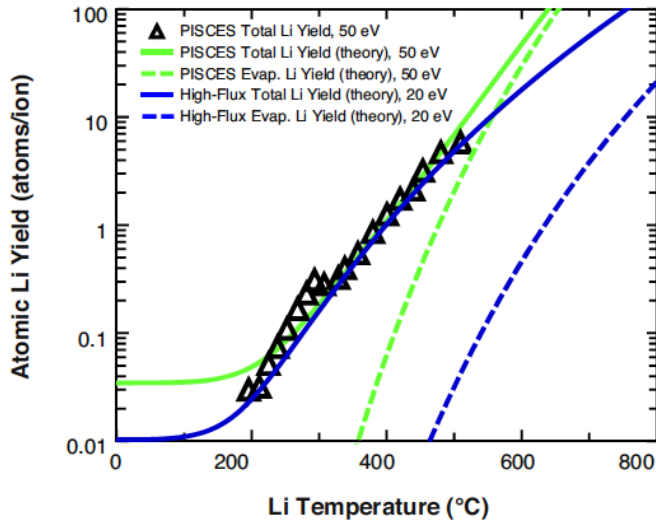
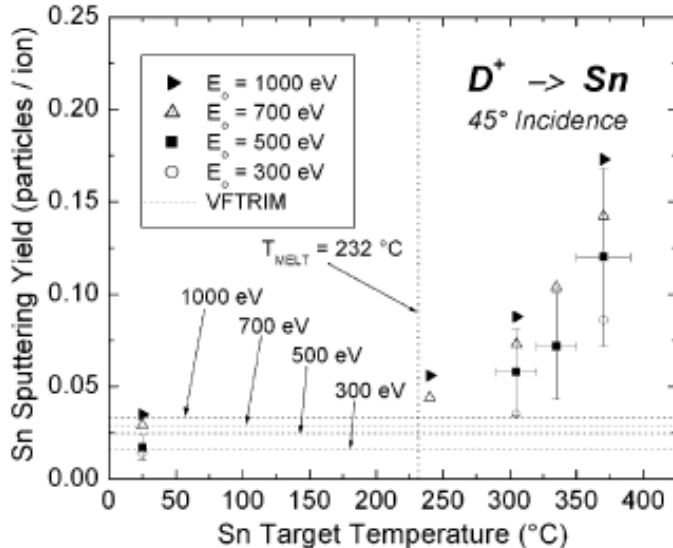


Fig. 2. Plot of the evaporative and total atomic Li yields vs. Li temperature for the plasma conditions presented in [18] ($50 \text{ eV}, 8 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1}$) as well as a high-flux, low-energy case ($20 \text{ eV}, 5 \times 10^{23} \text{ m}^{-2} \text{ s}^{-1}$) using Eq. (4).

Coventry et al. JNM (2004)



Adatom model:

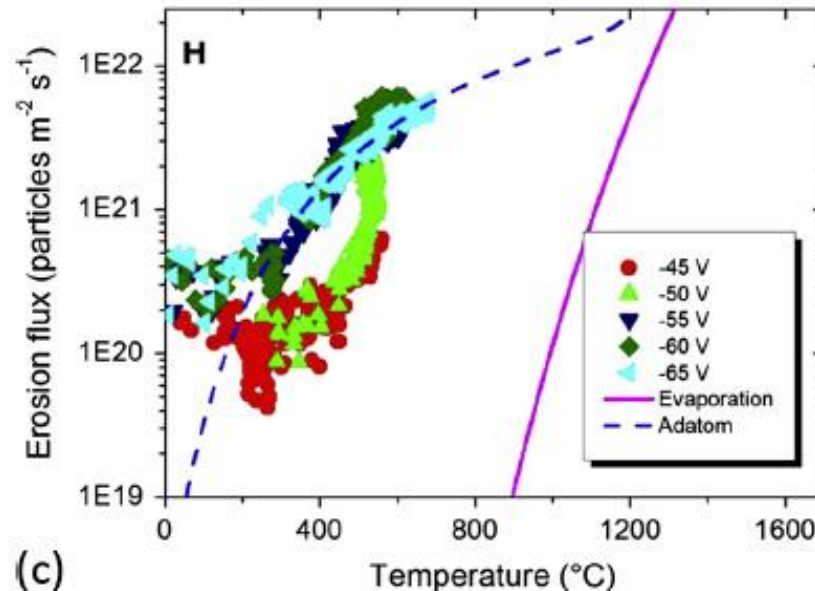
$$Y_{\text{thermal}}(T_{\text{surf}}) = \frac{A}{\sqrt{k(T_{\text{surf}} + B)}} \exp \left[-\frac{U}{k(T_{\text{surf}} + B)} \right]$$

$A=0.016, B=350 \text{ }^\circ\text{C}$ for Li

$$\text{Flux}_{\text{Sn}} = F_{\text{H}}^* (\gamma_{\text{Sputt}} + \gamma_{\text{Ther Sputter}}) + F_{\text{Evap}}$$

Also postulated for Sn. **No parameters available**

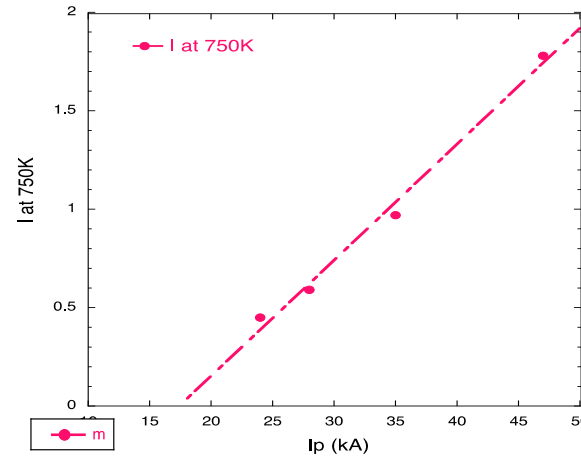
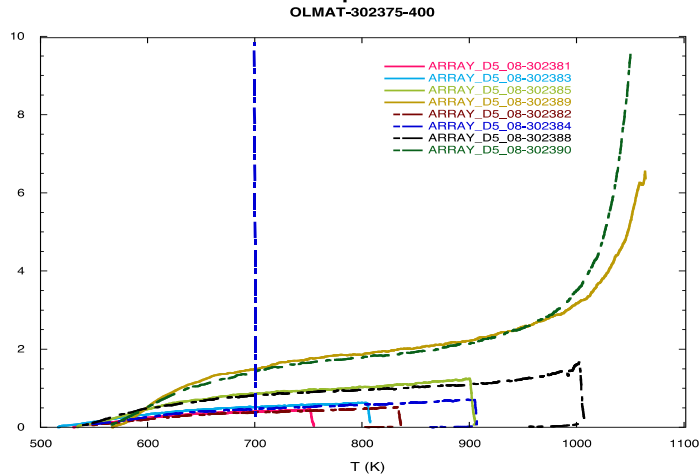
Morgan et al JNM 2015



Checking for model consistency

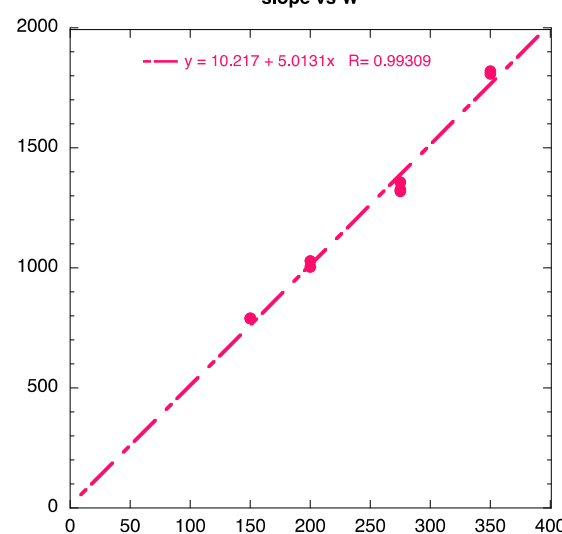
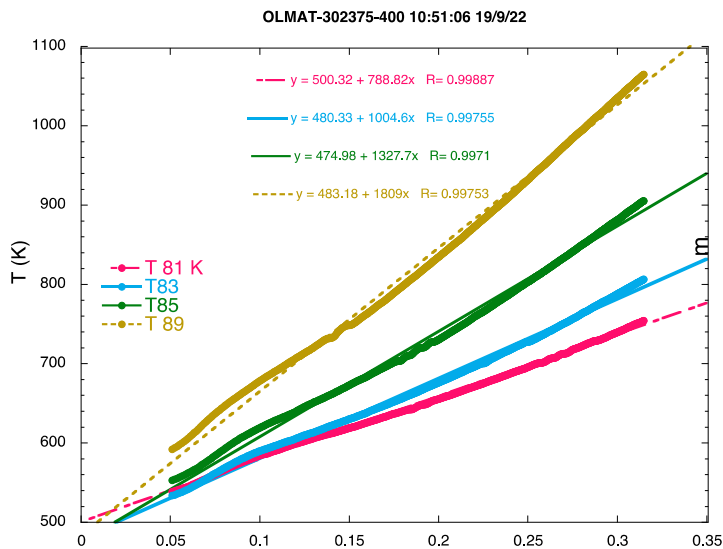


- At $T \ll T_{\text{evap}}$, $\text{Flux}_{\text{Sn}} \propto \text{Flux}_{\text{H}} \text{ (beam) @ } T \text{ fixed}$



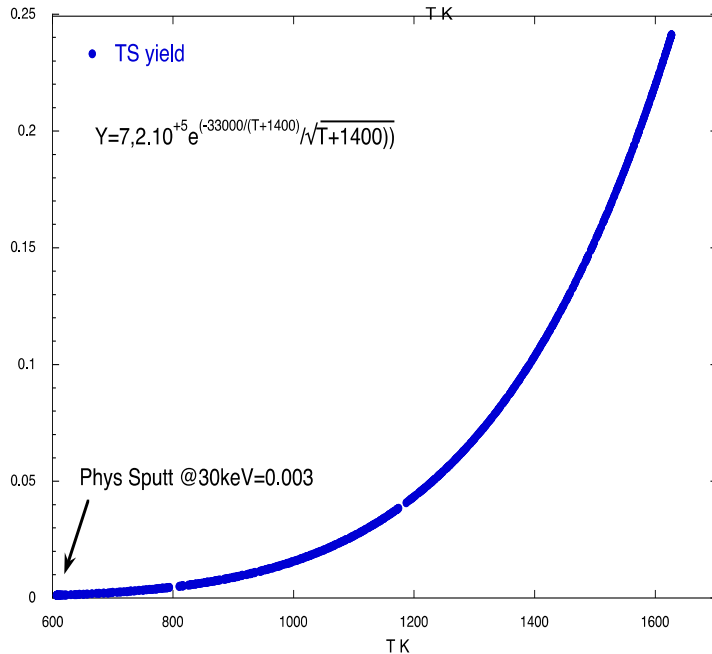
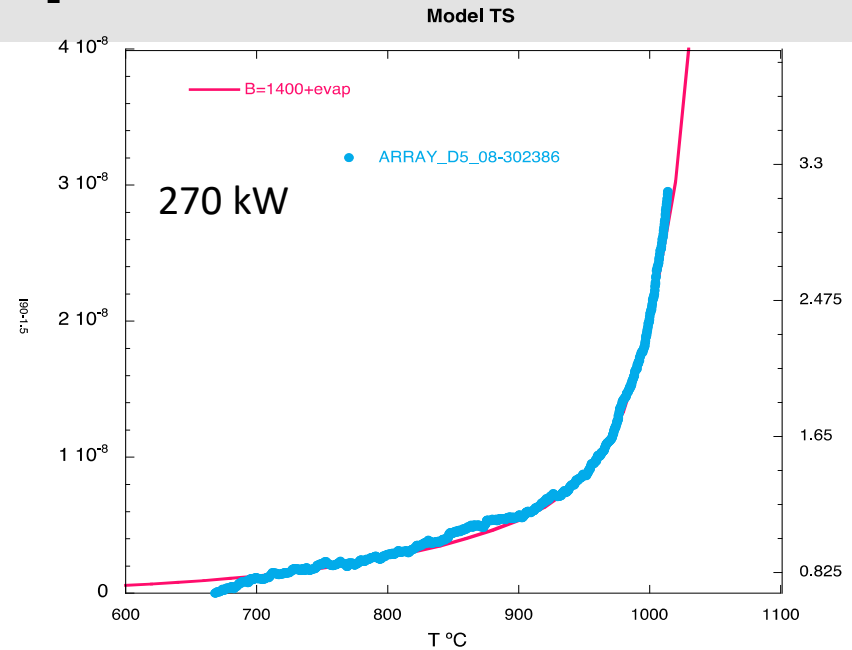
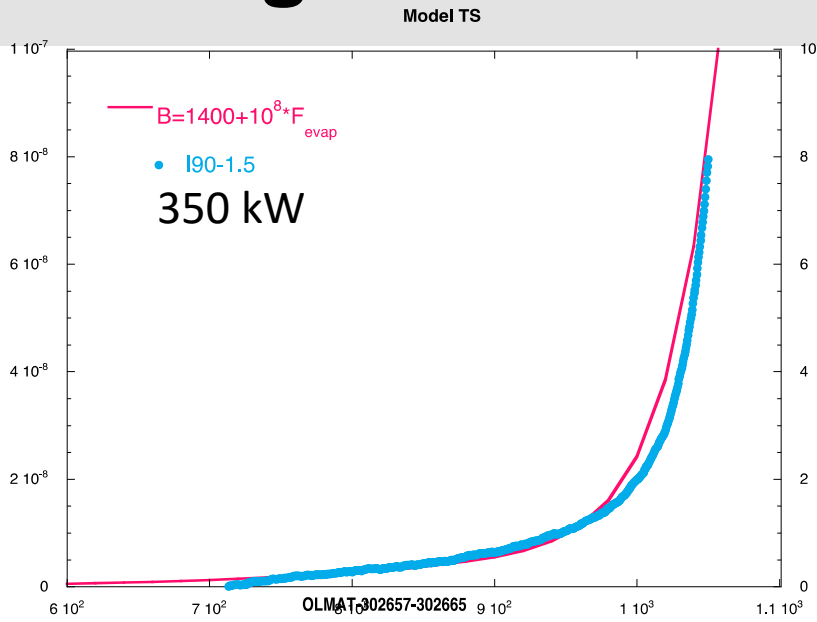
Constant excitation
Rate of Sn btwn
150-350kW

- Slope of ΔT vs $\sqrt{t} \propto Q \text{ (MW/m}^2 \text{) (slab model)}$



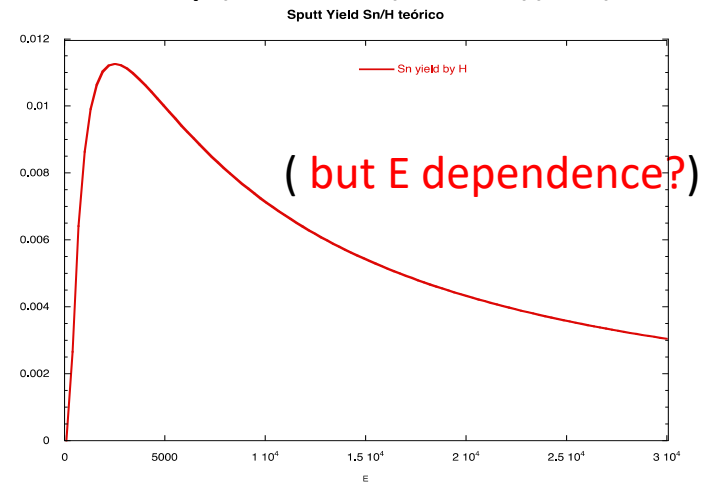
Good fitting to Slab model
Constant thermal
Parameters (C_p , ρ , κ)

Fitting to adatom expression



Sputt yield: $\gamma=7.2 \cdot 10^5 \exp(-33000/(T+1400)) / \sqrt{T+1400}$

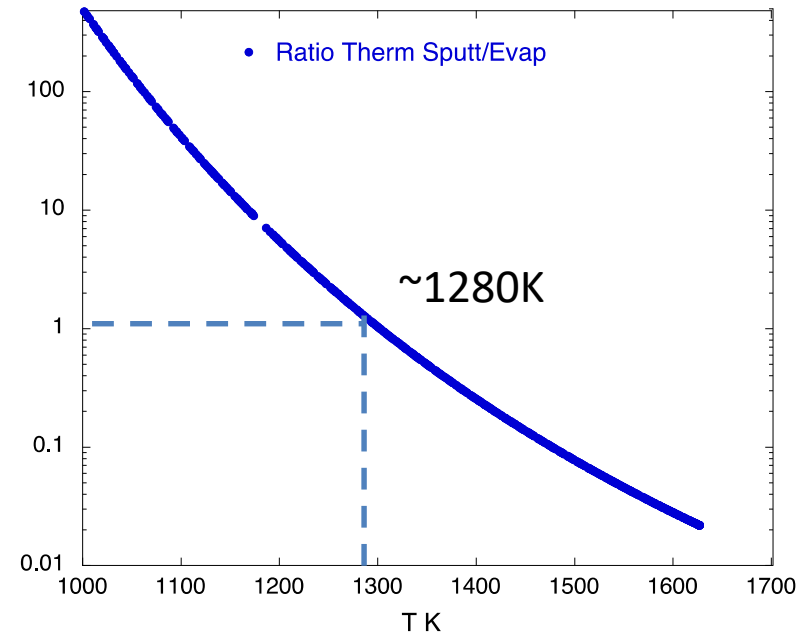
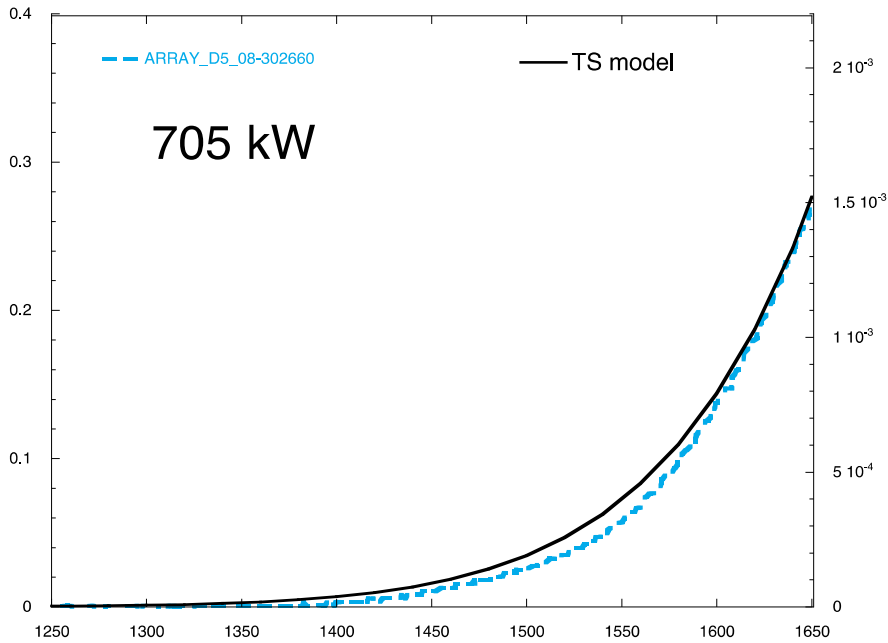
For Li: $\gamma=4.3 \cdot 10^9 \exp(-18400/(T+350)) / \sqrt{T+350}$



High Power/High T



OLMAT-302657-302665

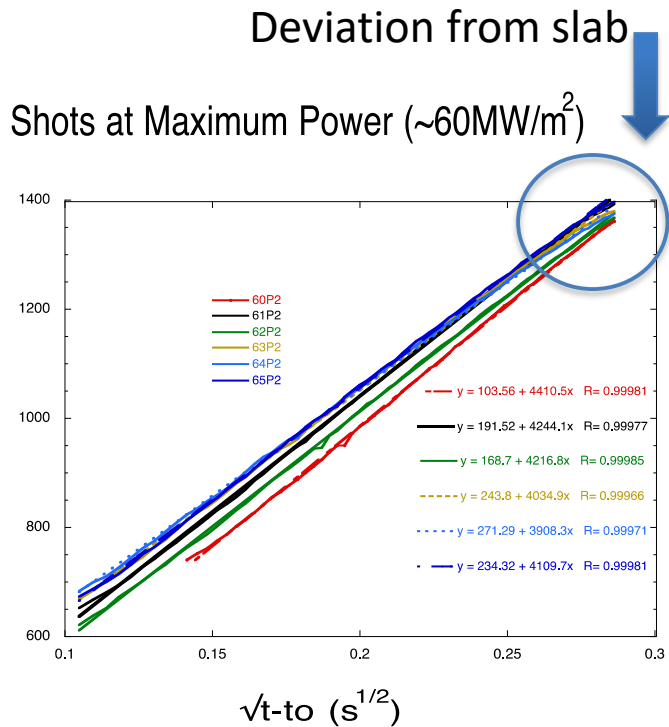


At maximum power (high T), fitting with evaporation only OK!!
At $T > 1300\text{K}$, evaporation dominates

Vapor Shielding

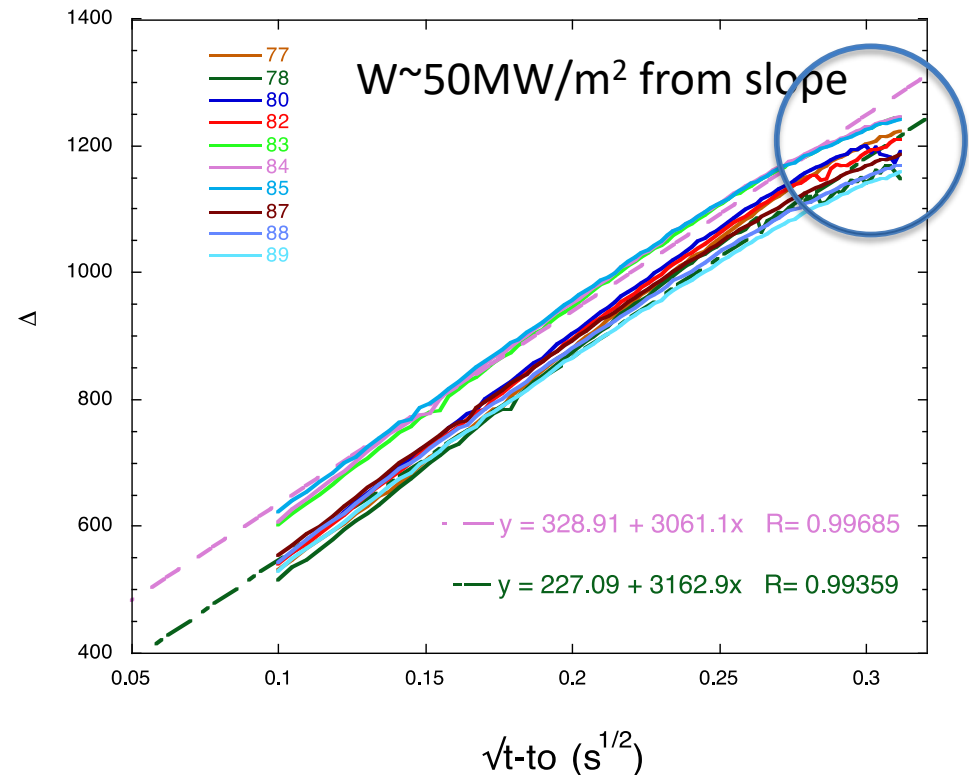


- For short pulses, no T clamping to be expected
- But..deviation from slab model?

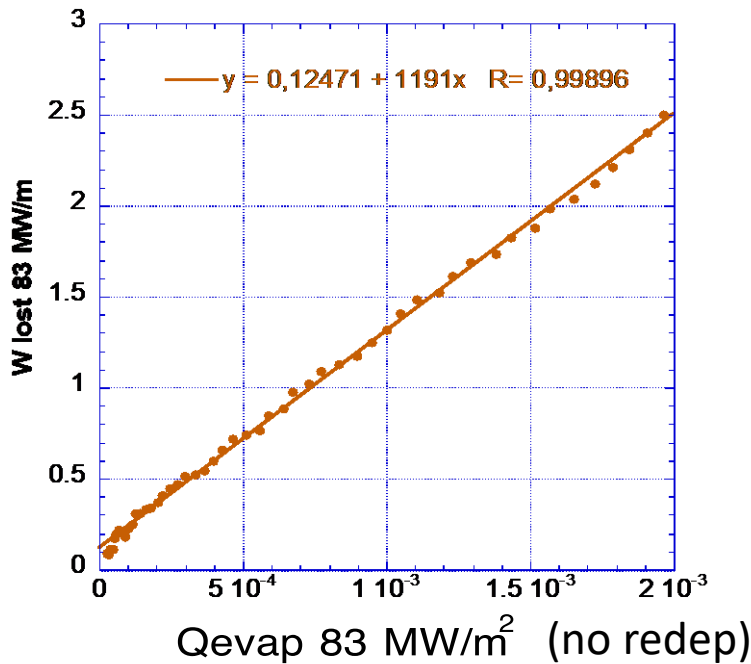


BUT: Window coating?

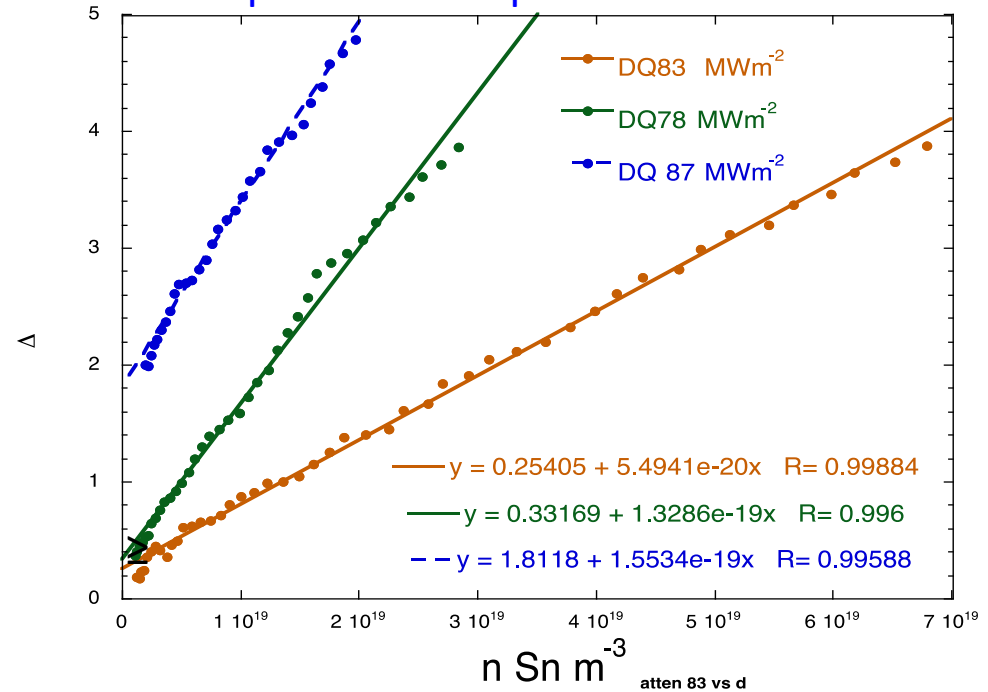
Repetitive discharges with retracted observation window at max V



Vapor Shielding: Parametric dependence



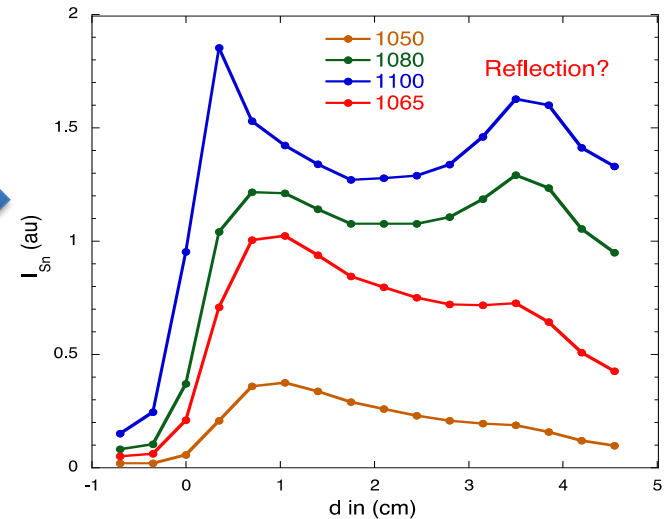
Dispersion of slope → Te variations?



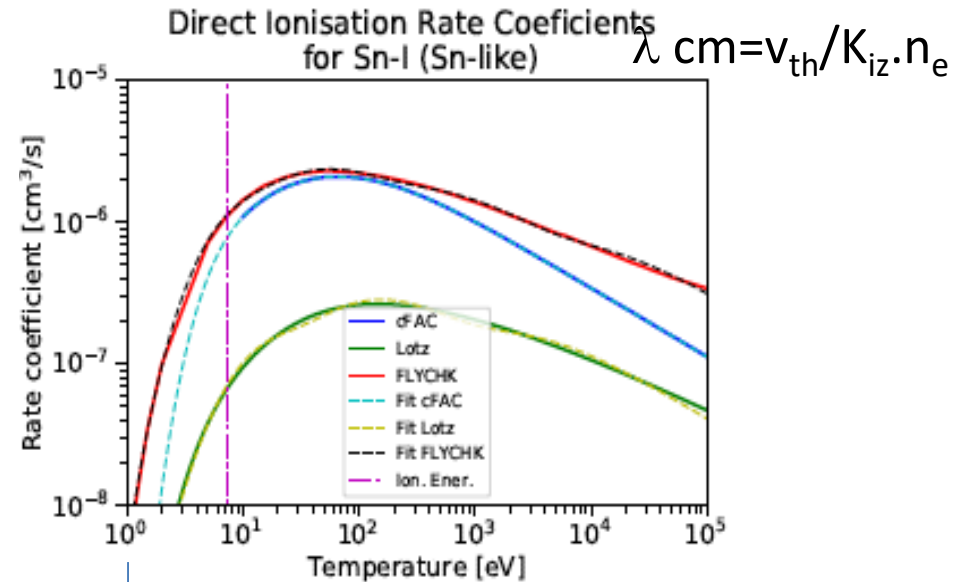
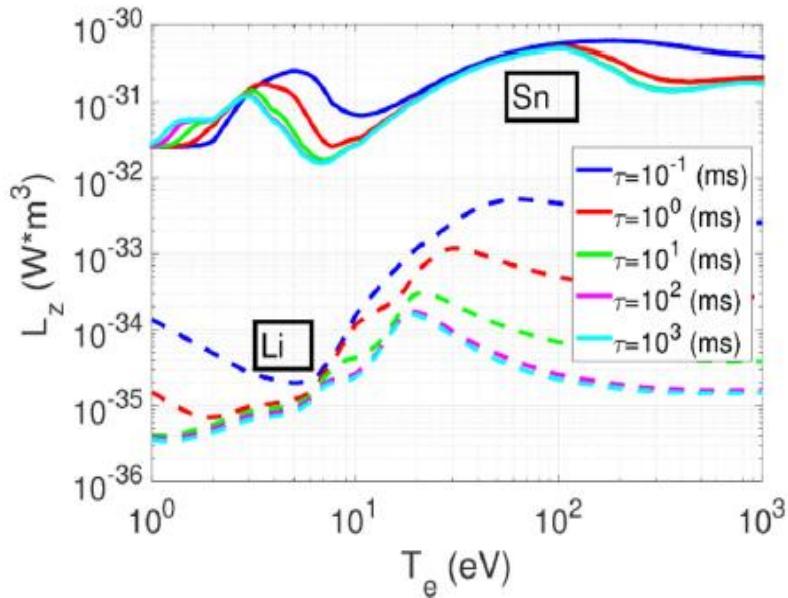
• $Q_{rad} \sim L_z \cdot n_e \cdot n_z$

From slopes, at $n_e = 5 \cdot 10^{18} \text{ m}^{-3}$ and $\delta = 2.5 \text{ cm}$

$L_z > 4 \cdot 10^{-31} \text{ W/m}^3$



Analysis of Results



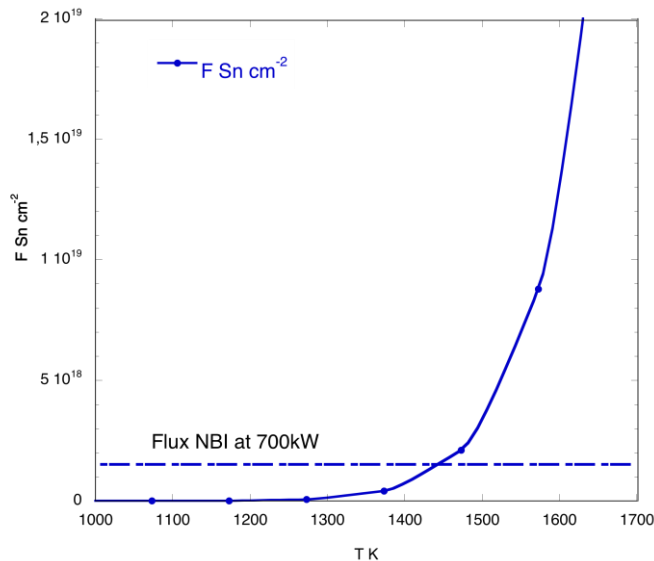
From Putterich et al. 42nd EPS Lisbon 2015

If Sn attenuated in ablation plasma

$$K_{iz} \sim 3 \cdot 10^{-9} \text{ cm}^3/\text{s} @ 2-3 \text{ eV.}$$

Warning!!: What will be the composition of local plasma
At $n_{\text{Sn}} \gg n_{\text{D}}/T$?: pure Sn plasma?? → Enhanced Radiation?

For DEMO: $F \sim 10^{24} \text{ m}^{-2}$, → $T > 1800 \text{ K}$



Conclusions



- The new HHF Facility for testing divertor material candidates for a Fusion Reactor, OLMAT, has been used to investigate elemental processes in LM exposed to very high powers. Target plasmas (plume) were characterized by OES and LPs
- Thermal sputtering of Sn by 30keV H beam was characterized in the range of $T=MP$ to 1700K. The functionality predicted by the adatom model was confirmed.
- Evaporation overrides sputtering at $T>1300K$ for the highest heat fluxes.
- The onset of Vapor Shielding was detected at $T\sim 1600K$
- **A linear dependence of dissipated power on Sn density was found beyond the heat of vaporization regime.**
- This regime corresponds to Sn evaporative fluxes equal or greater than NBI fluxes.
- The values deduced for Lz and K_{iz} Sn are in very good agreement with AM bibliographic data.
- A pure Sn plasma could be deployed at the divertor target under high T conditions, thus enhancing the VS effect.
- More experiments ongoing with the help of a high power fiber laser.

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