Studies of Vapour Shielding Physics in the OLMAT Facility. Applications to the LMD EuroFusion Project

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The views and opinions expressed herein do not necessarily reflect those of the European Commission.

OUTLOOK

- Background. Motivation
- The OLMAT Project
- AM+LM Physics to address

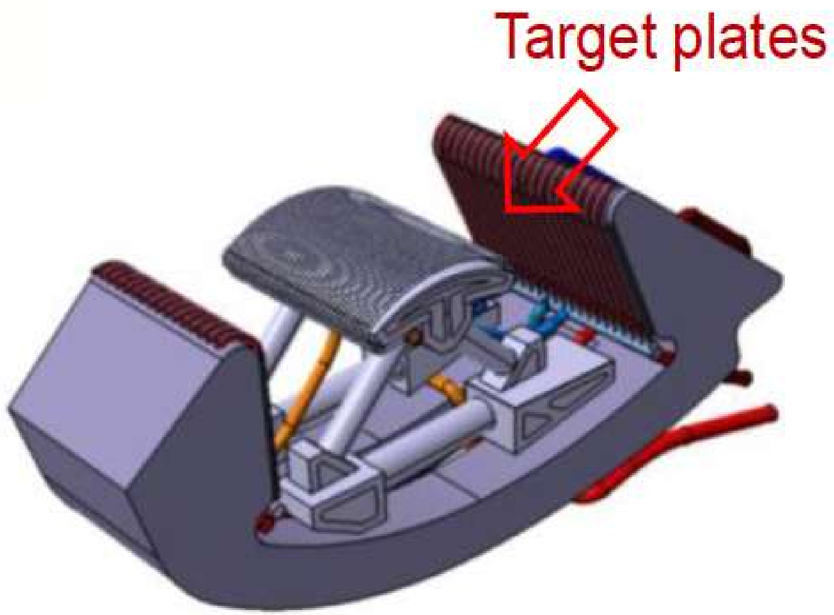
Power Load issues

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



Alternative: Liquid Metals in High Flux areas

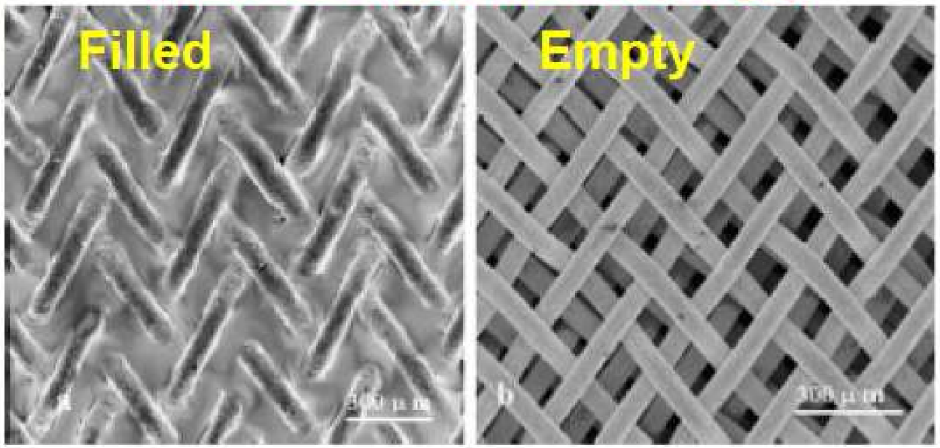
- ✓ *No permanent damage (self healing)*
- ✓ *Can be recirculated (power and T extraction)*
- ✓ *Vapor shielding*

Proposed designs

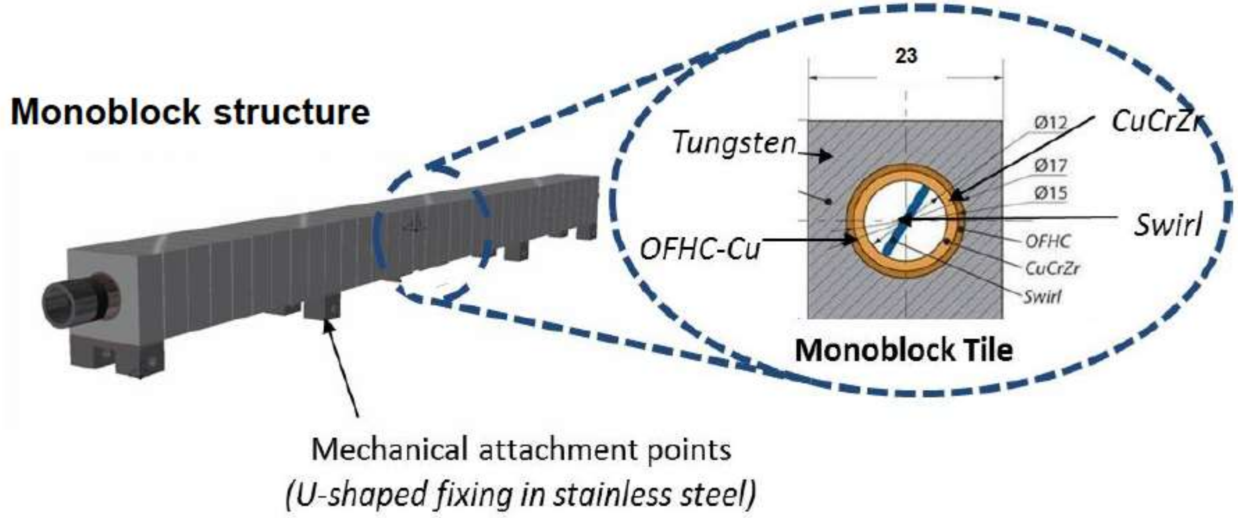
- ✓ Free flowing LM: continuous pumping out heat and particles
  But: MHD instabilities, magnetic viscosity → Splashing!
- ✓ Grooved surfaces, slow motion: Uniformity, Wetting issues!
- ✓ **Capillary forces:** liquid metal is bonded to the surface, inhibit instabilities.

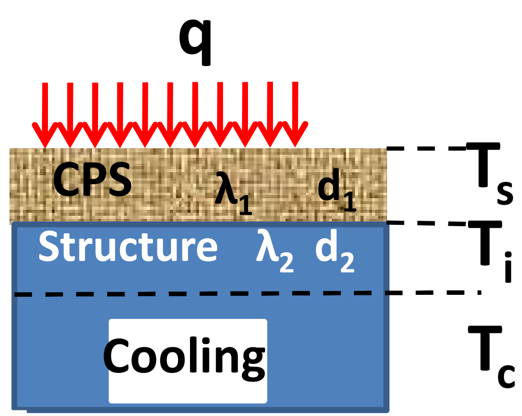
Idea

First test with Mo mesh [5]



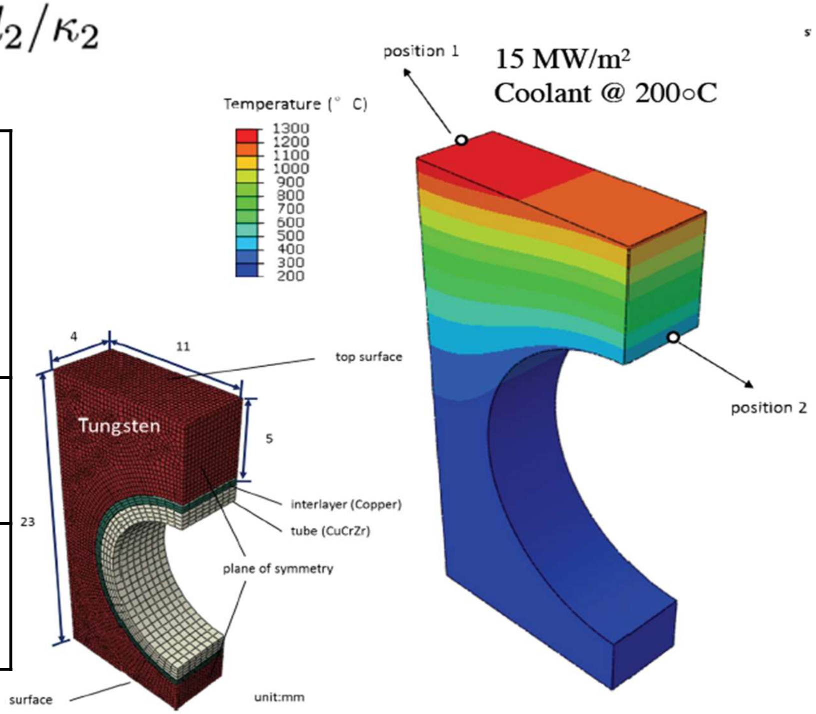
ITER design+Surface modification





$$q = \frac{T_{sur} - T_{cool}}{d_1/\kappa_1 + d_2/\kappa_2}$$

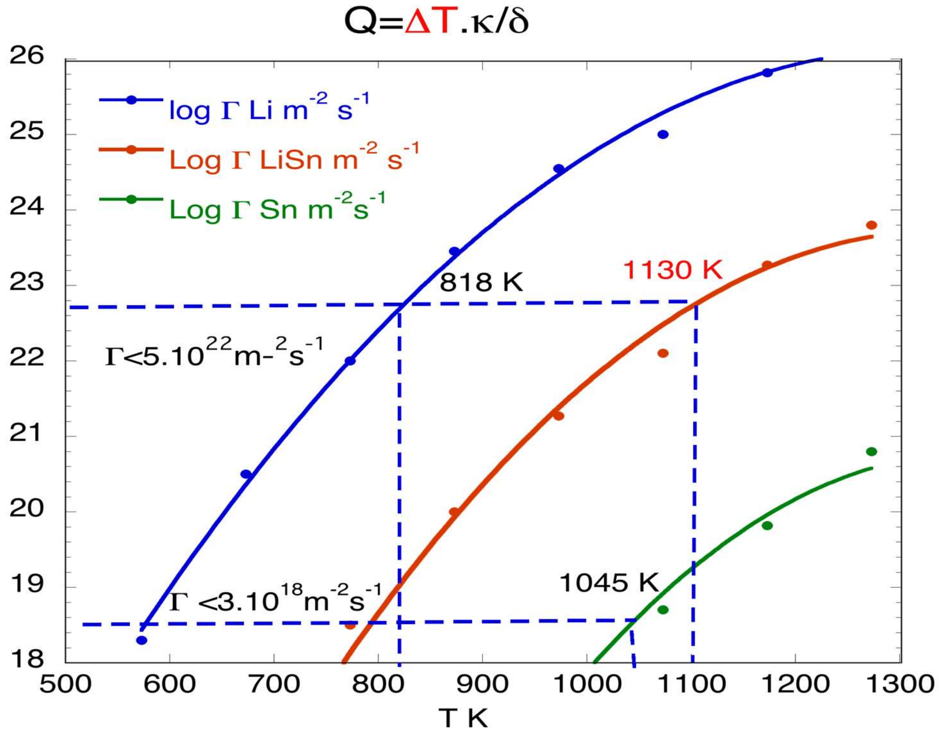
	Ts (°)(T_w=150) 1% FLUX	d_1(mm) (CPS)	d_2(mm) (struc)	P (MW/m²)
Tin optim.	1277	1	3	28.75
Li optim.	480 (no redepos)	1	3	8.25



TABARES. Vapour Shielding CRP. VIENNA 2019

Which LM?: Comparative analysis

Γ max from code calculations:



Which LM maximizes conductive heat exhaust?

\+

- *H retention*
- *Material Compatibility*
- *Cooling issues*
- *Close Loop/refilling*
- *Wetting*
- *CPS design parameters*
- *.....*

Many answers already available from previous works

+ sputtering

Integration issues:

Core plasma radiation/dilution
water cooling?→ Maximum Liquid Li in vessel
Need of impurity seeding?
Stability of LiSn alloys…

Target Design with LM protection

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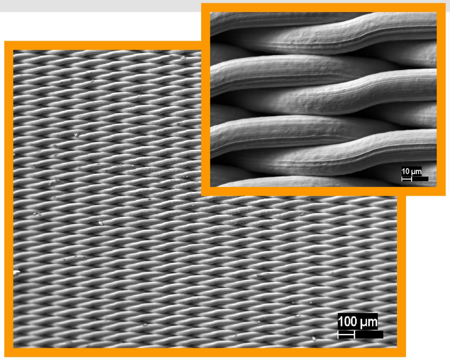
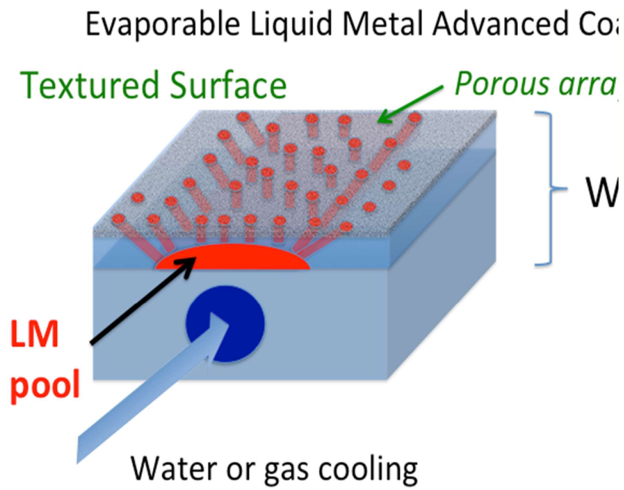
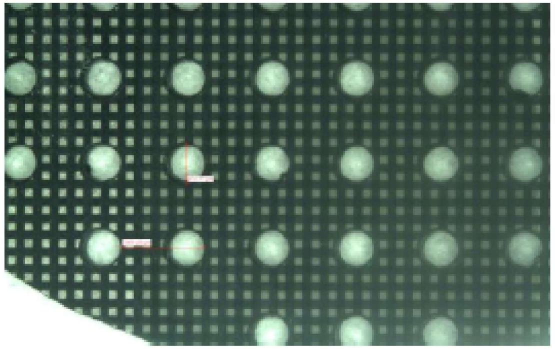


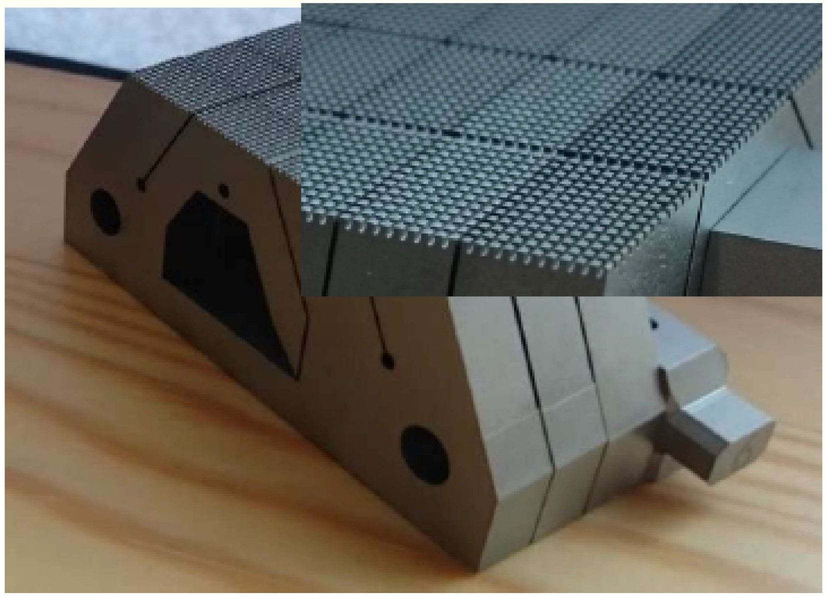
Standard CPS structure

"ELMAC"



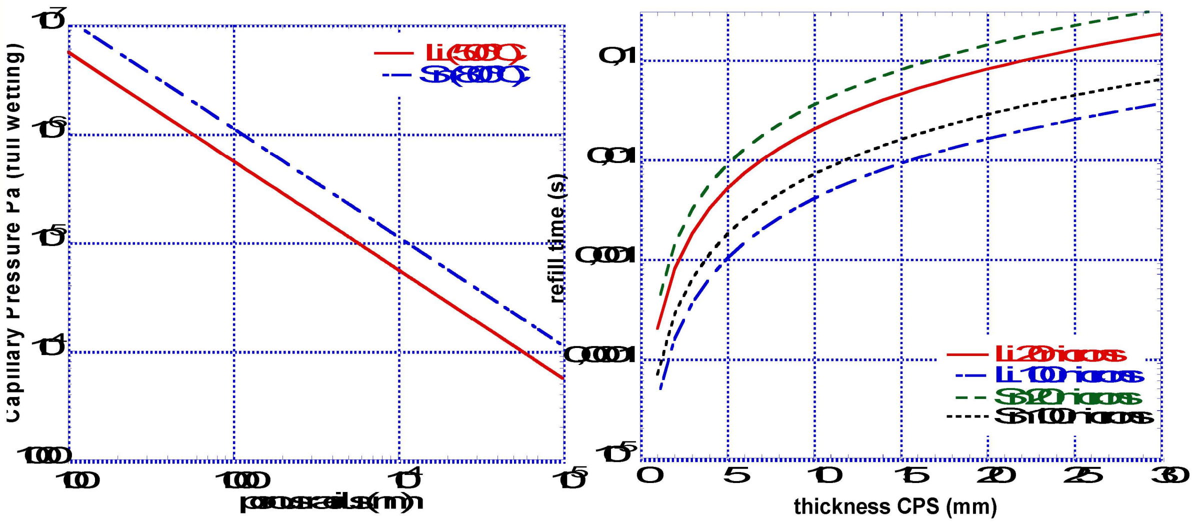


200 µm Channel +1mm pore



Prefilled Modules, NSTX

Holding Force+ refilling time



The OLMAT Project

Alternate use of TJ-II as a test bed and a magnetized fusion device for LM alternative target research

Project developed in three (overlapping) phases

Phase 1) NBI exposure of LM prototypes. Comparative studies (<200ms pulses, no ELMs)

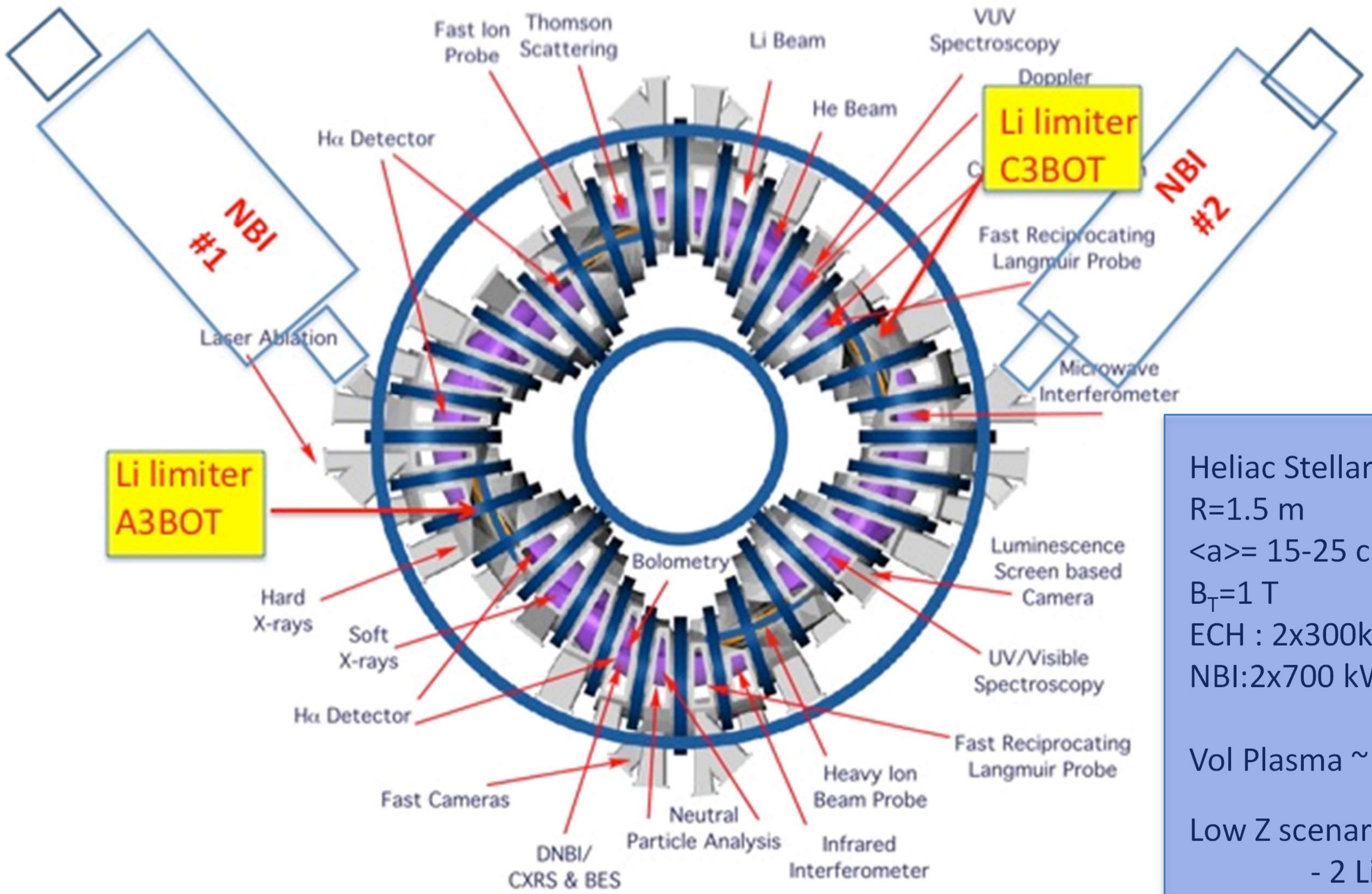
Phase 2) Addition of ELM-like loads (Laser pulses)

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

Phase 1)

- LM (Li, Sn , LiSn) and CPS structures tested

RESOURCES. TJ-II



Heliac Stellarator 4 periods
R=1.5 m
<a>= 15-25 cm
B_T=1 T
ECH : 2x300kW,53.2 GHz
NBI:2x700 kW, >30 KeV

Vol Plasma ~ 1m^3

Low Z scenarios :
- 2 Liq Lithium Limiters
- First Wall Boronization
- Vacuum Lithiation

SPECIFIC FEATURES OF THE OLMAT PROJECT

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European Facilities

Hot Plasma+ LM:

- FTU: CLL, no NBI, narrow ports
- ISTTOK: no NBI, small tokamak
- COMPASS-U: Under design

EF Test Facilities:

- GLADIS: No Li operation
- JUDITH: e^- beam. Raster.
- PSI-2/ JULE: No Li operation
- MAGNUM: Not fully devoted to LM experiments. Small spot.

OLMAT Features

- Fully devoted to LM research
- Large exposed area
- DEMO relevant heat loads
- Power Dep. profile adjustable
- Long (150ms-few s)+short (<1ms) pulses
- High repetition loads (1shot/2min+kHz ELM) (fatigue eff.)
- Rotatable, refilled, heated + cooled sample

NBI systems in TJ-II

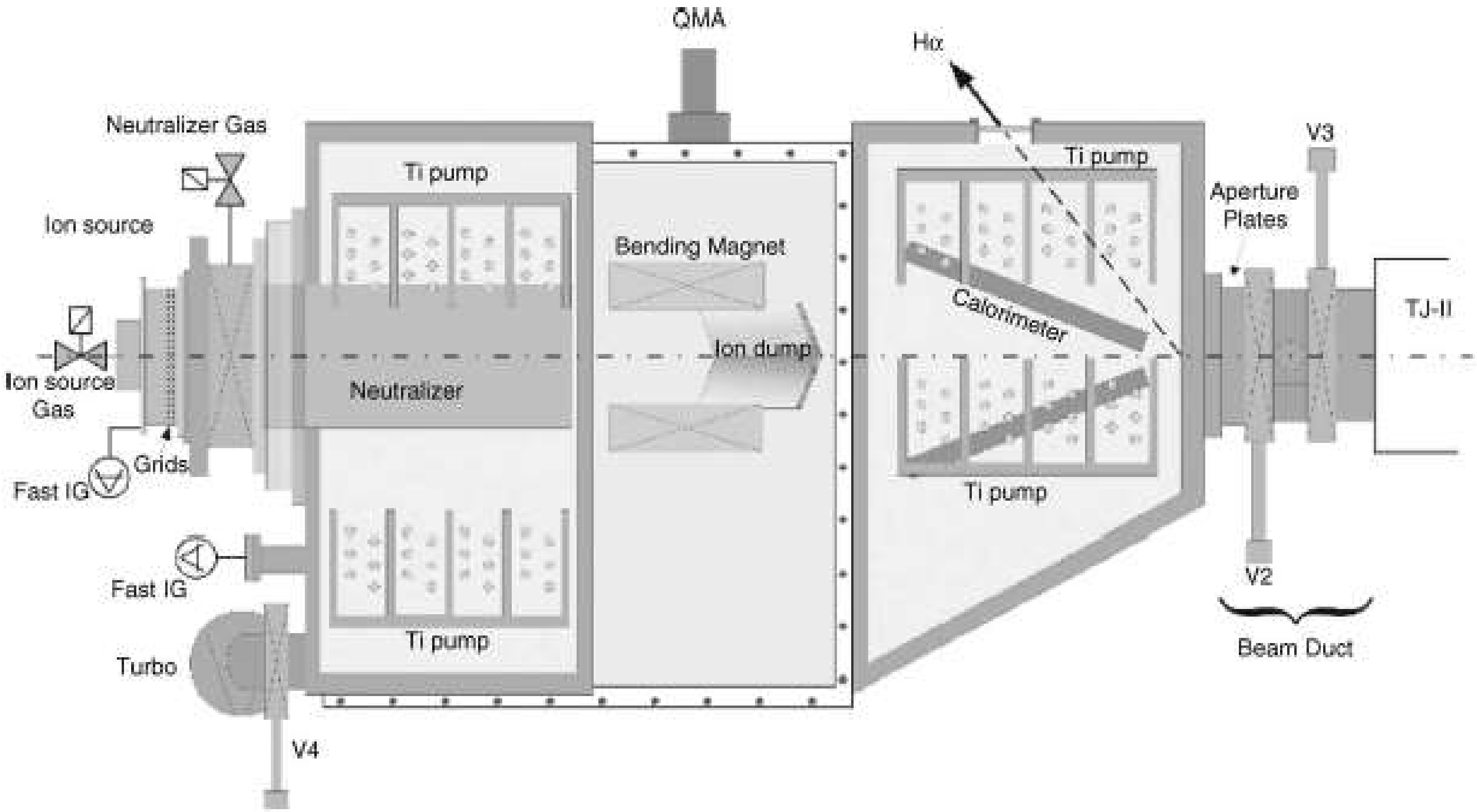
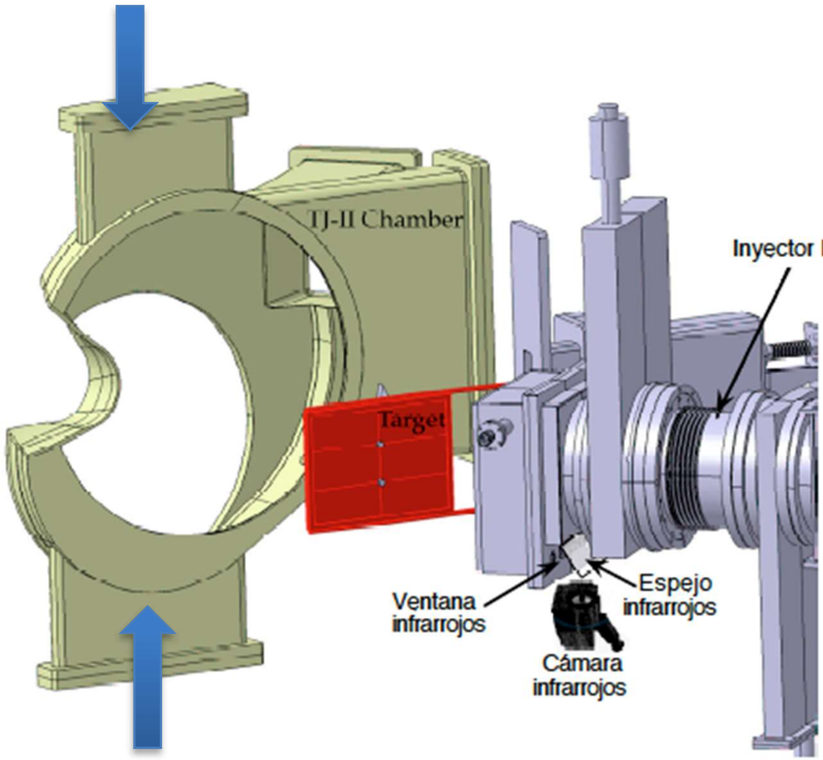


Fig. 1. Schematic of one injector with its various components and beam apertures along the beam line and duct.

- ✓ 30 cm diameter duoPIGatron ion source.

Beam spectrum: 55% E_0, 25% $E_0/2$ and 20% $E_0/3$

RESOURCES. NBI



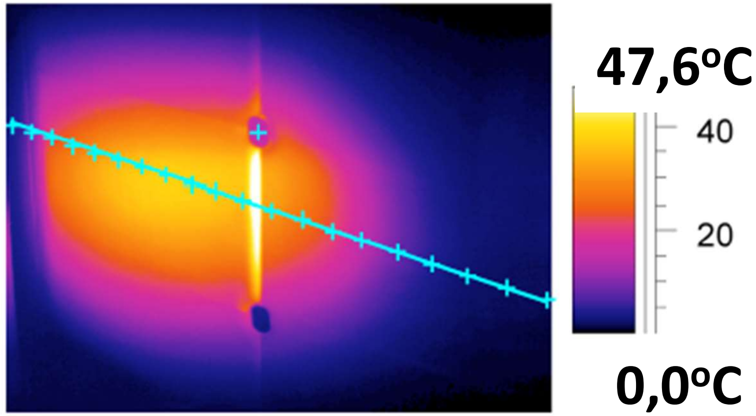
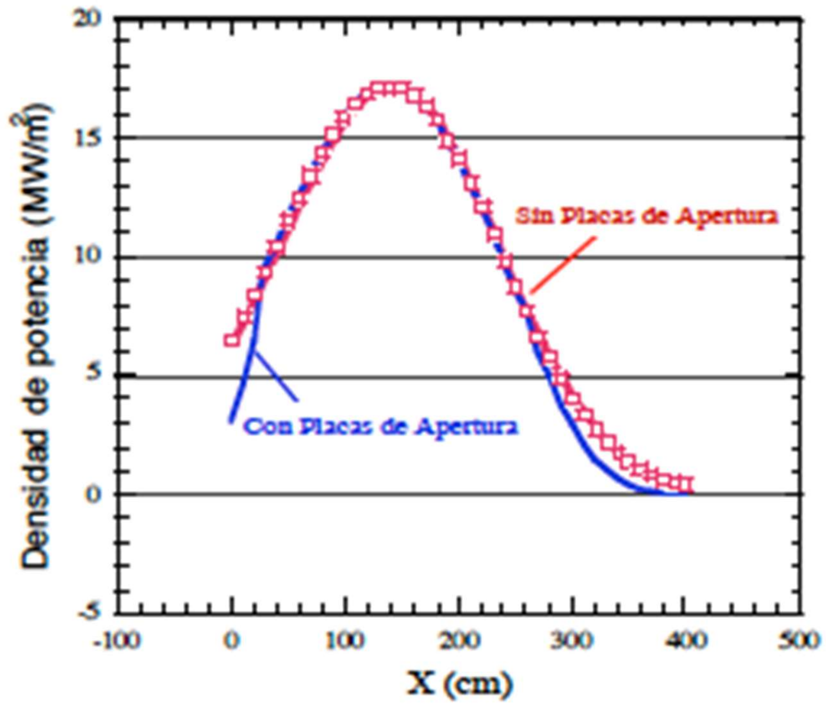


Figure 3: IR image of the Target Calorimeter after a NBI shot

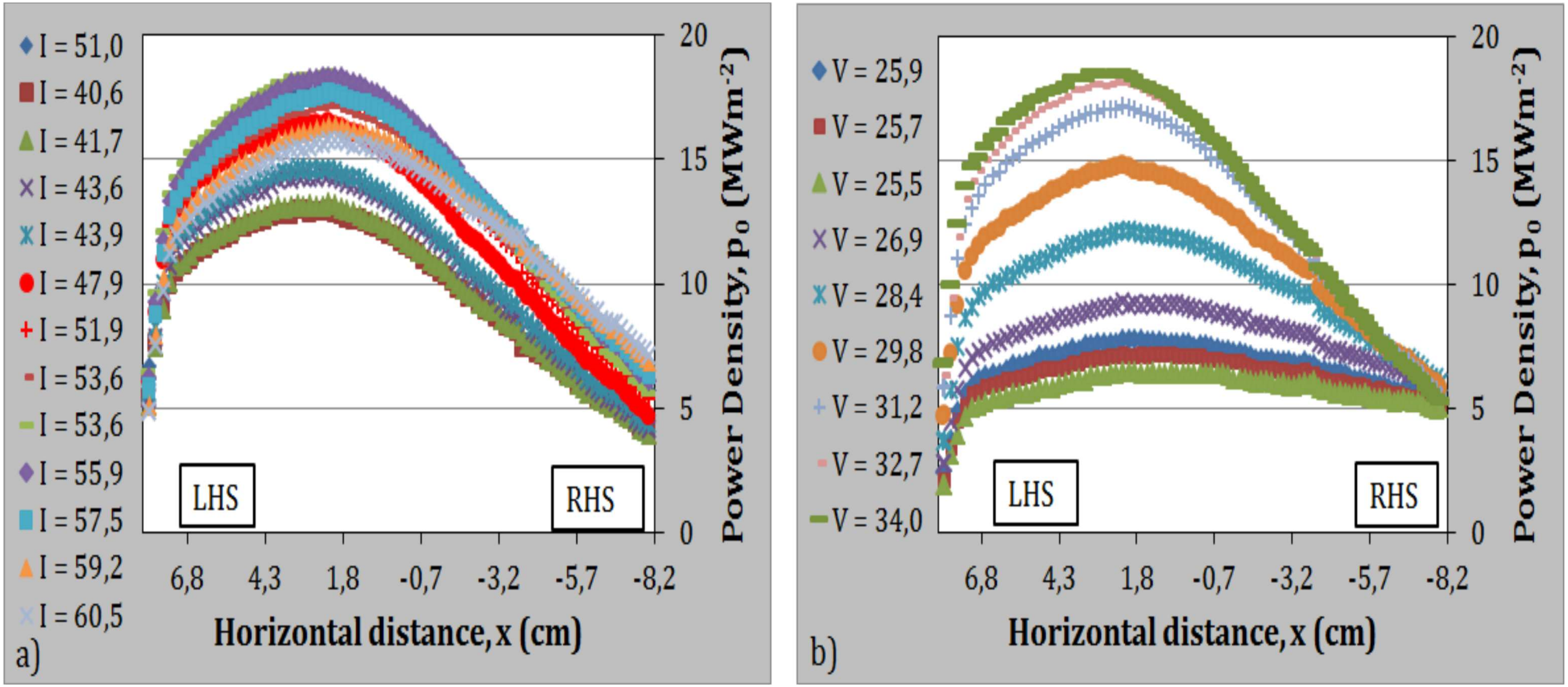


NBI present Characteristics

Working gas	Hydrogen
Accel voltage	35 keV
Accel current	60 A
Decel voltage	1.5 keV
Decel current	10 A
Arc voltage	150 V
Arc current	1200 A
Pulse duration	150 ms
Duty cycle	≤ 1 %
Gas throughput	20-40Torr.l.s^{-1}

Possible operation w/o neutralizers: +35%

Power density achievable

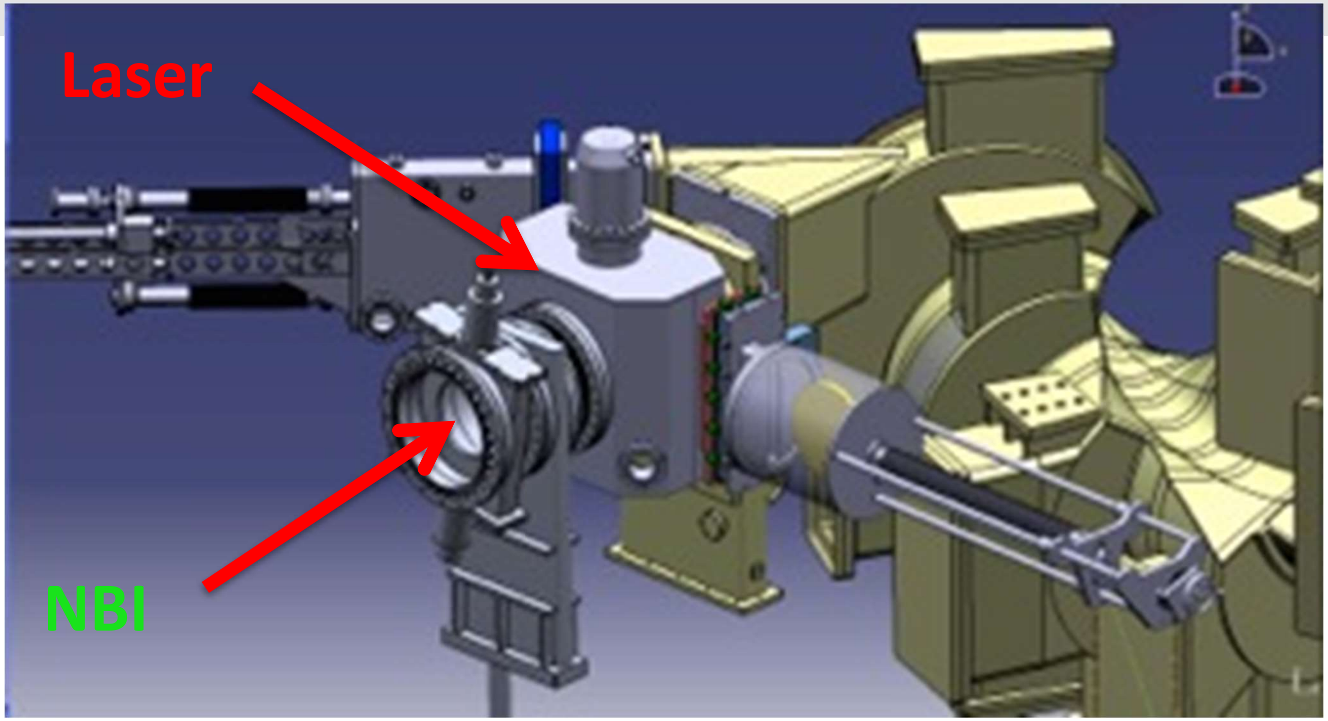


Parametric Scans in I& V

I_b at constant V_{acc}: Peaked Q profiles

V_{acc} at constant I_b: From flat to peaked

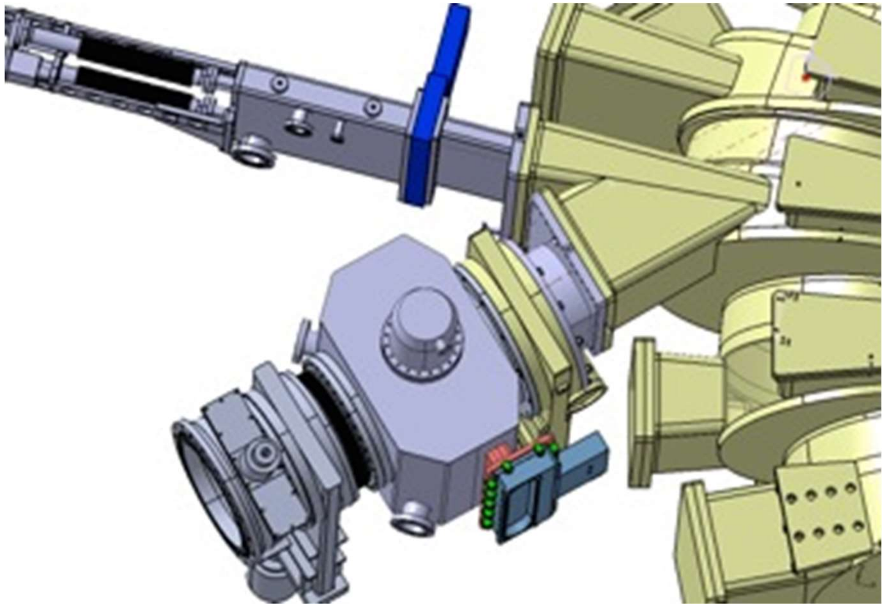
Final Design



Pulsed Laser :

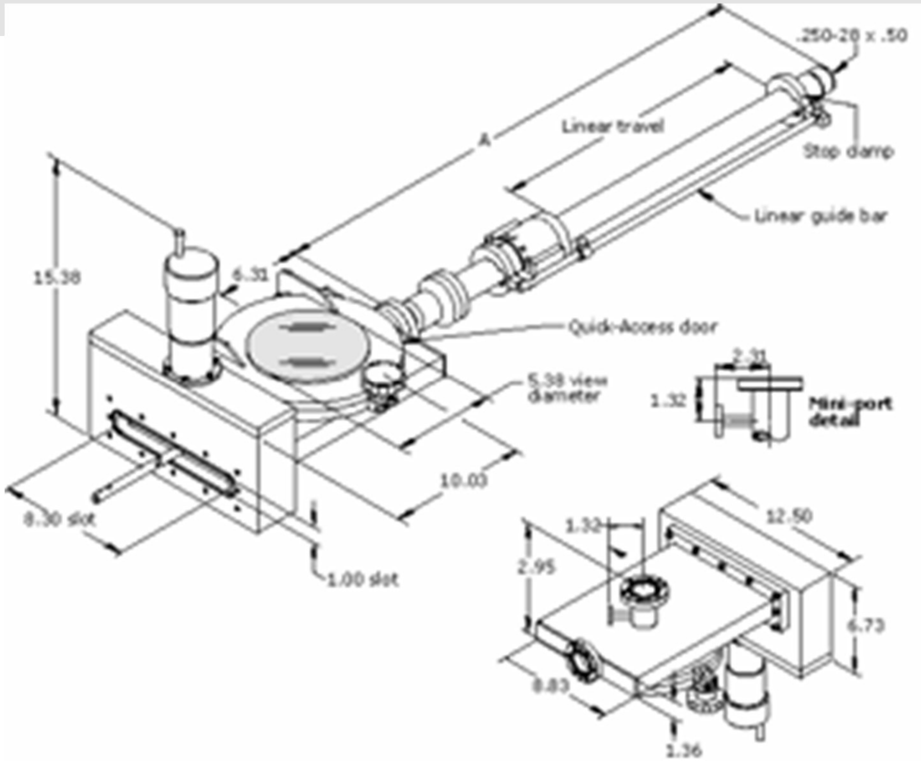
✓Fiber type

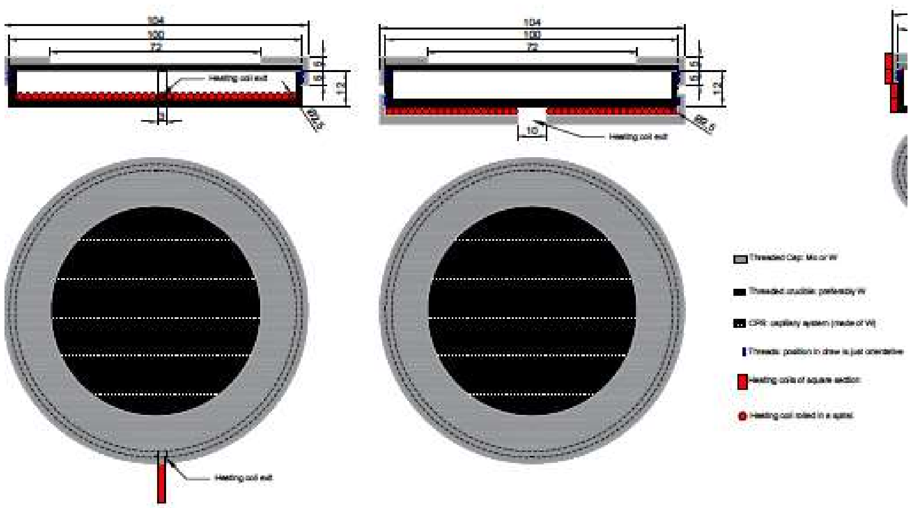
✓0.5 GW/m2



- Devoted exposure chamber
- Sample preparation pre-chamber
- Linear manipulator w long drive heating and *rotation*
- Sample holder: 250 mm diam.

Chamber design





DIAGNOSTICS

- OES: Stark broadening, Impurity, line ratio (He beam), etc…
- Langmuir probes
- TCs
- Calorimetry
- IR camera
- Pyrometers
- Laser detachment?
- LIBS? (NdYag Laser available)
- VUV spectroscopy
- Bolometry
- SXR
- ….

Expected deliverables :

✓Performance of Liquid Metal-based targets during slow transients up to Power Fluxes of 20 MWm^{-2}. LMs: Li, Sn and LiSn. Comparative study

✓Impact of the CPS design on its ability to withstand high power fluxes.

✓Combined effect of ELMs and high, steady, power fluxes on the LM target.

✓In situ determination of the surface refilling time for each CPS structure (KHz laser)

✓Effect of H content on theses parameters at levels below the sat. solubility limit.

✓Stability of LiSn alloys in the presence of strong redeposition.

✓Redeposition efficiency of ejected material.*

✓Radiation of the local plasma at high concentrations of LM constituents.*

✓ AM Physics of vapor shielding phenomena

* *Extrapolation to divertor plasmas through modeling*

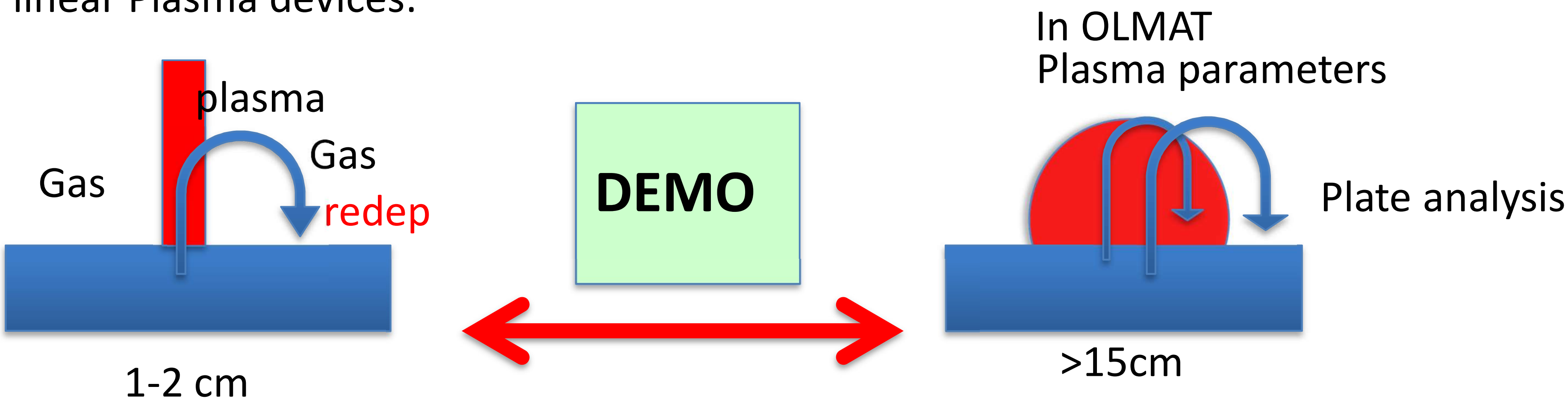
EXAMPLES

- **Vapour shielding/ T clamping**

- It has been proposed that P_{vapLM}~P_{plasma} leads to T clamping (vapour shielding)
- In DEMO P_{plasma}:10-100Pa
- For Li: 612-722 ºC, For Sn: 1000-1250 ºC
- P_{nT} in OLMAT up to 45 Pa: Different possible combinations of Flux+ Energy/ptcl.→ Different plasma parameters. Address vapour shielding physics

- **Redeposition**

In linear Plasma devices:



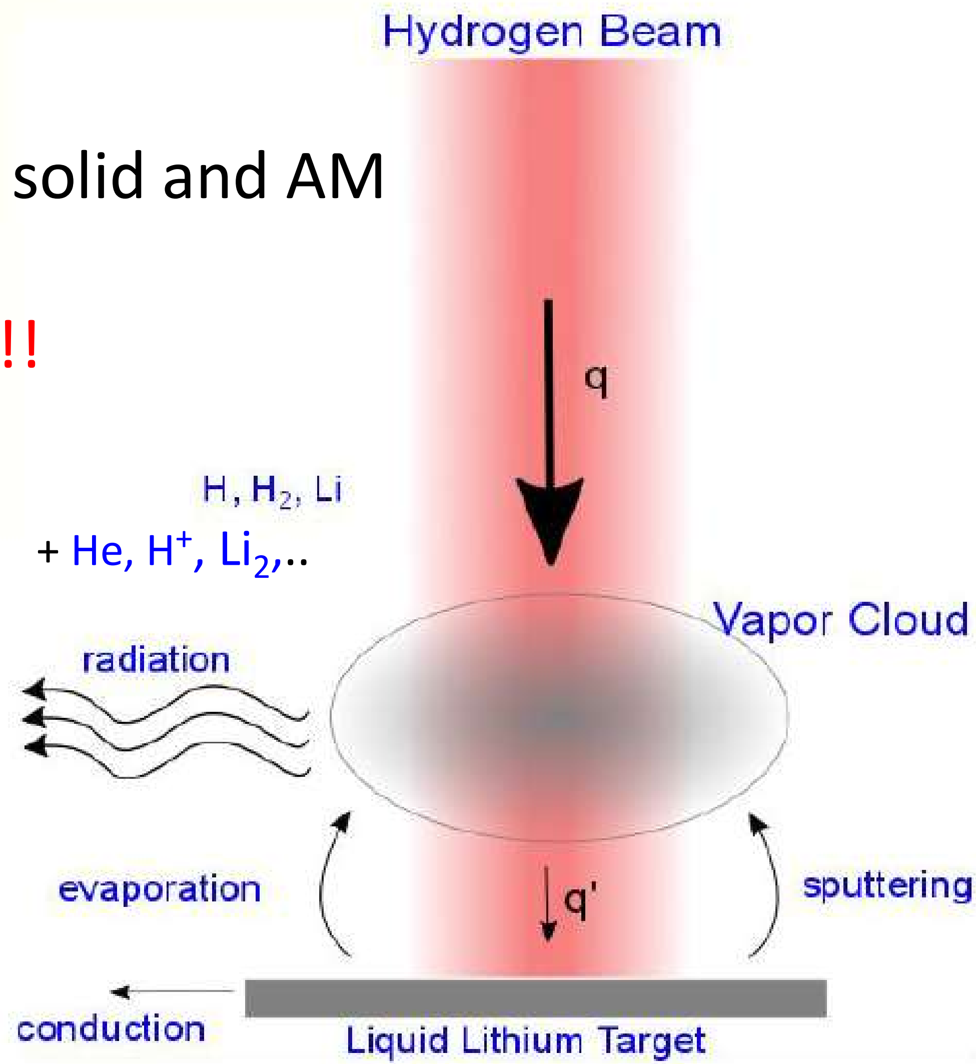
AM+LM Physics to address

Idea: use liquid metals in regions with largest loads (target plates).

- ✓ **Self-healing:** no damage from neutrons, transients, no erosion, etc.
- ✓ **Vapor shielding:** produced vapor protects underlying material.

Complex interplay of solid and AM +Plasma Physics

Not fully understood!!



VS Models

Three models analysed by Skovordin et al. (PoP 2016)

- 1) Reduction of power by “optical depth” of VS Plasma
- 2) P_{rad} ~N of ptcls in VS Plasma
- 3) Size of Vapour cloud matters

$$E_{max} \approx \sqrt{\frac{4C_p\rho\varkappa}{\pi}}\,\frac{E_{ev}}{k}\,\frac{\sqrt{t_{pulse}}}{\Lambda}.$$

$$\Lambda \sim \ln \tau_{pulse} \sim 2\ln G_{1,2,3}.$$

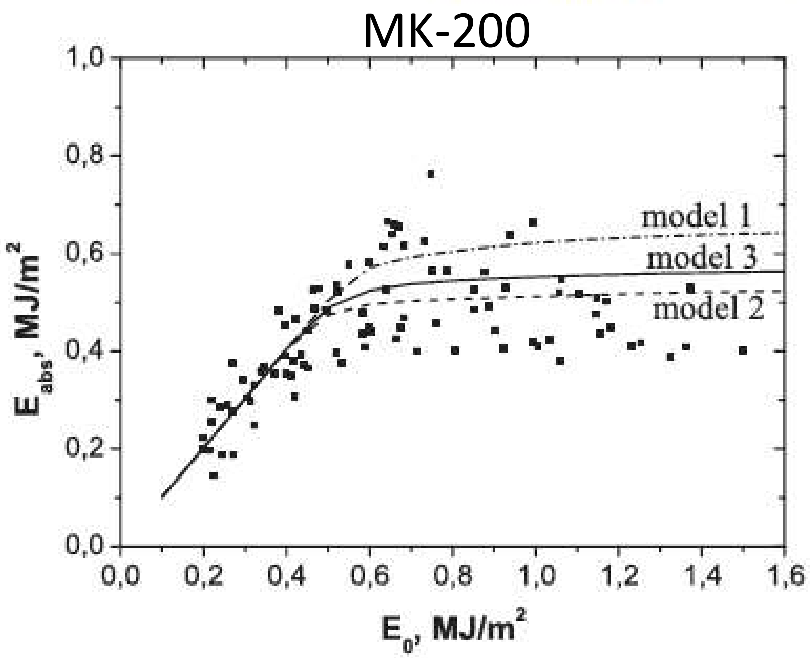
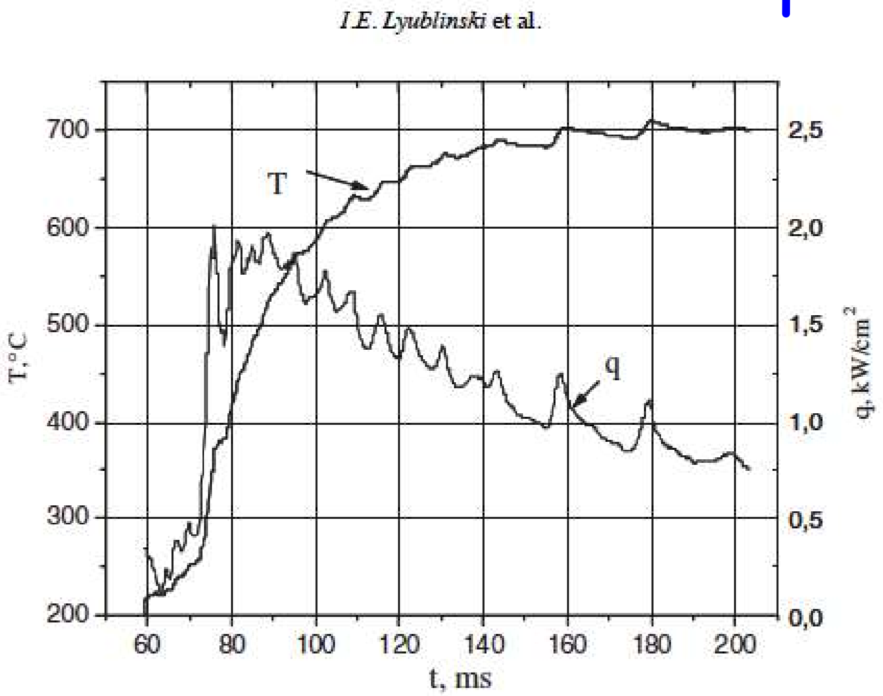


FIG. 3. The energy absorbed by the tungsten target over the energy stored in the incident plasma flow. Dots represent the experimental data obtained at MK-200 pulse plasma accelerator; curves represent the result of numerical calculations performed for three different models described.

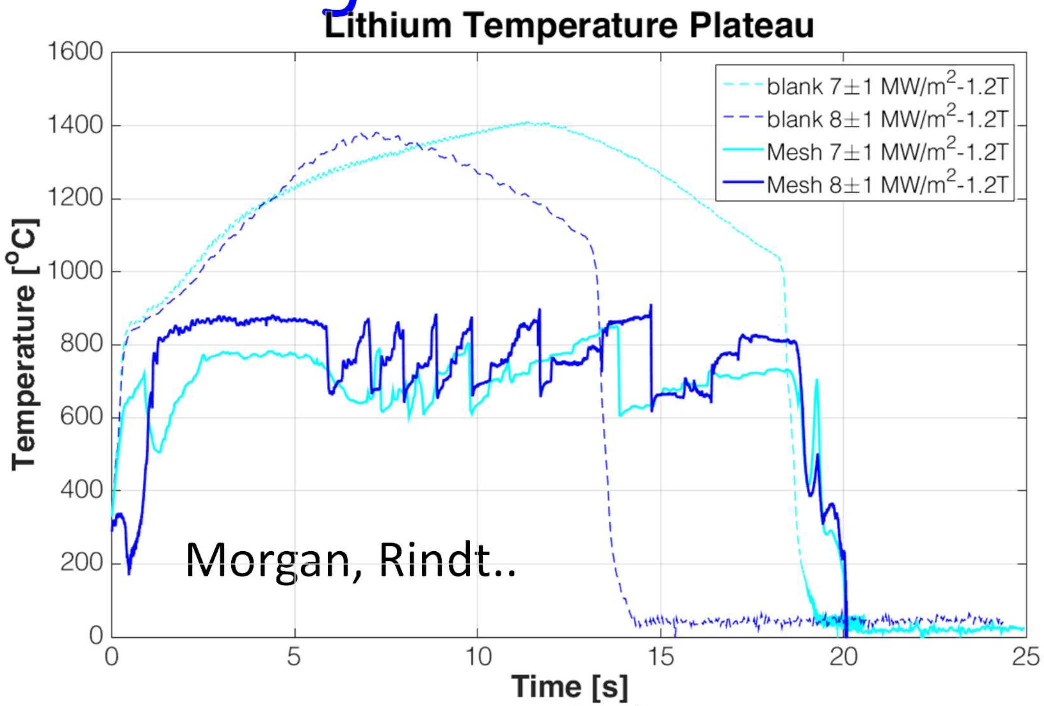
E_{max} abs not a validation parameters for the model. *Look for total evaporated flux.*

✓ *PISCES B: Light impurities (Be) penetrate the plasma and induce cooling. Not for W, Mo*

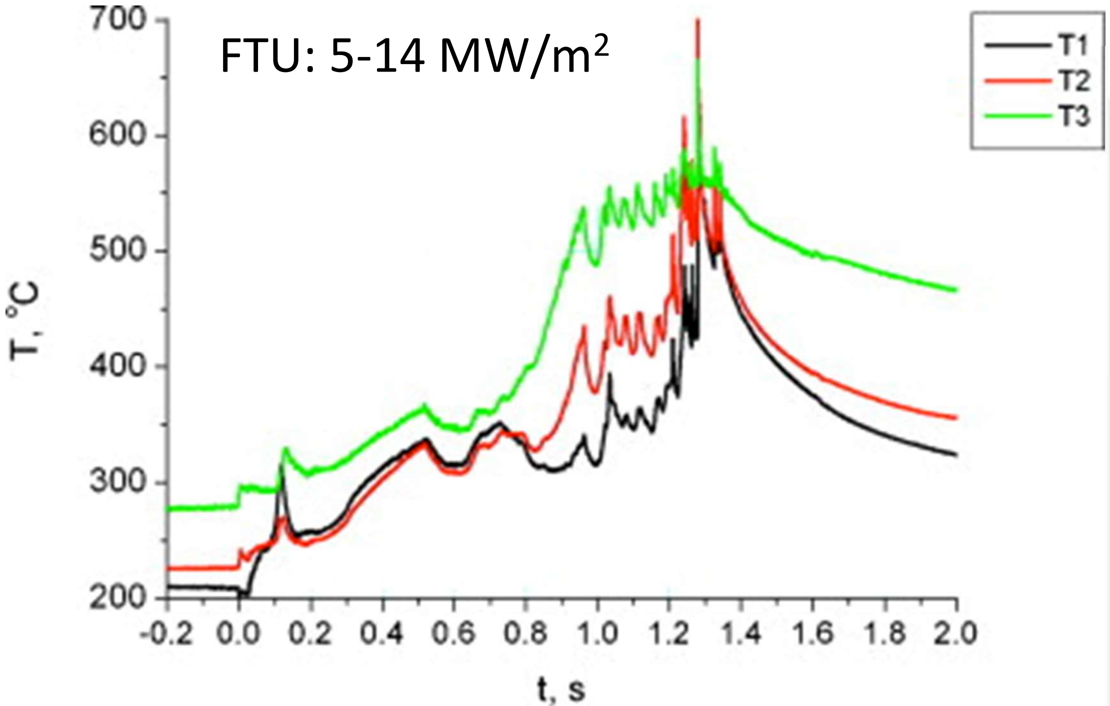
Vapour Shielding in Li



T-10: >10MW/m²



Magnum PSI: 7-8 MW/m²

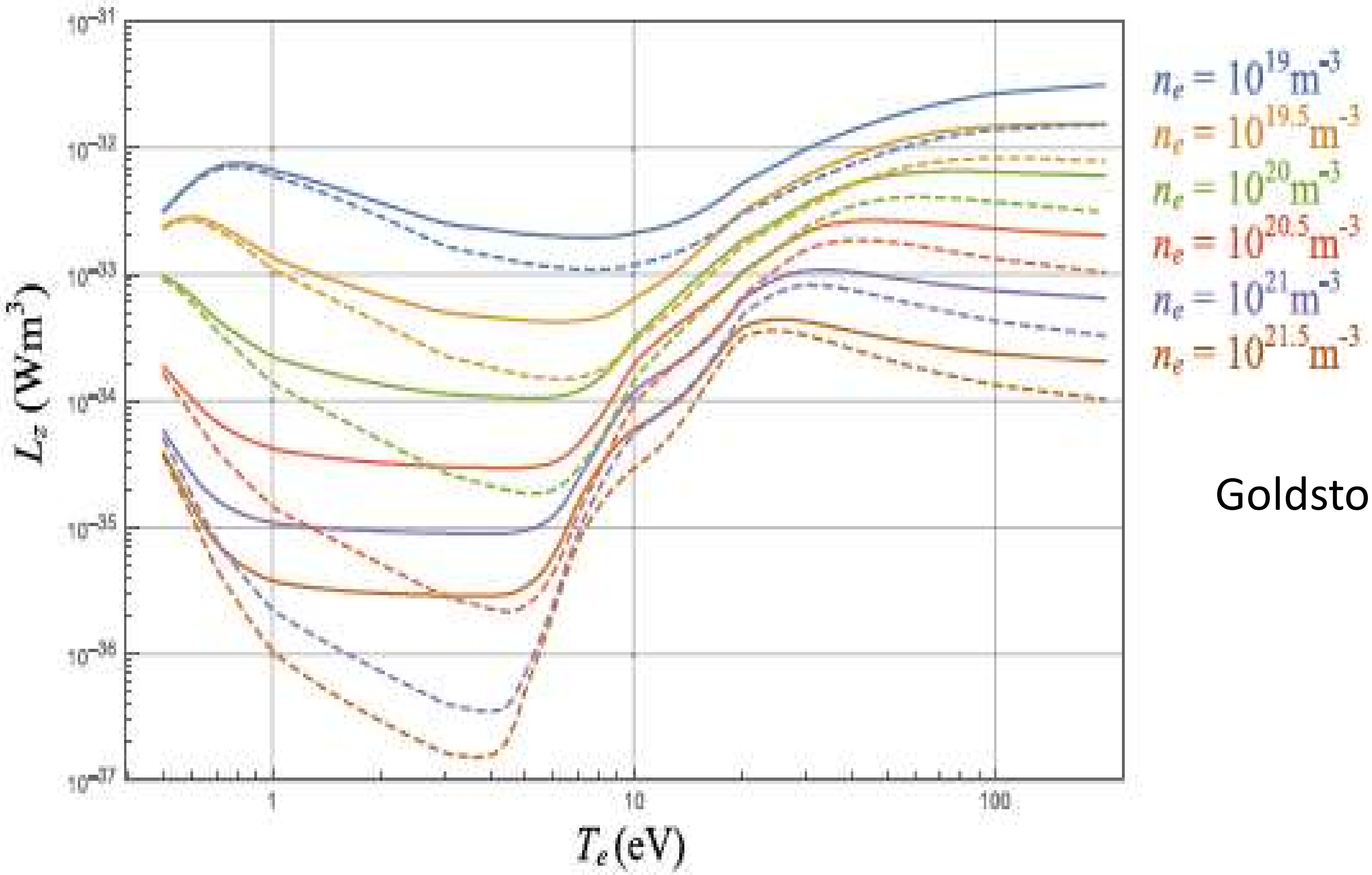


Γ_{Li} :100x (600-900ºC)

Why Tw higher in Divertor-like plasma?

- ✓ P_{rad} by Li ions?
- ✓ P plasma?
- ✓ Plasma species (H vs He)
- ✓ Mag Field effects?
- ✓ Etc..

CR Model Li. Fixed tau



Goldston 2016

Figure 3. ADAS-based collisional radiative L_Z versus T_e for $\tau_Z = 10^{-4}$ s. Dotted lines are for radiation losses only, solid lines include power committed to ionization.

Only e- collisions included!

CR non coronal eq.

Lazarev EPS 99

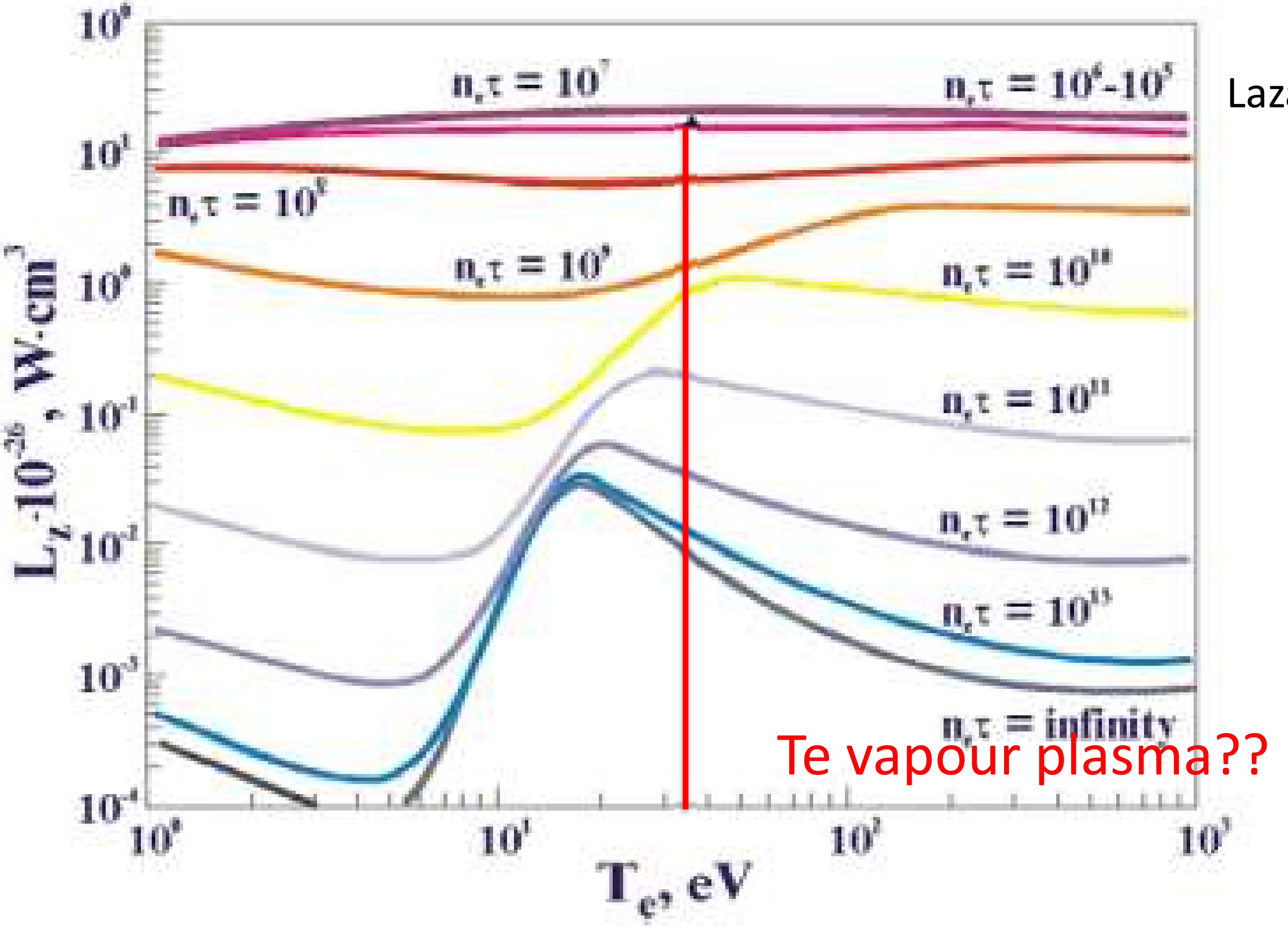


Figure 3. The Li non-equilibrium and coronal radiation ($n_e\tau$ = infinity) power per one atom and one electron as a function of electron temperature and 'non-stationary parameter $n_e\tau$'.

Sensitivity to Atomic Radiation models

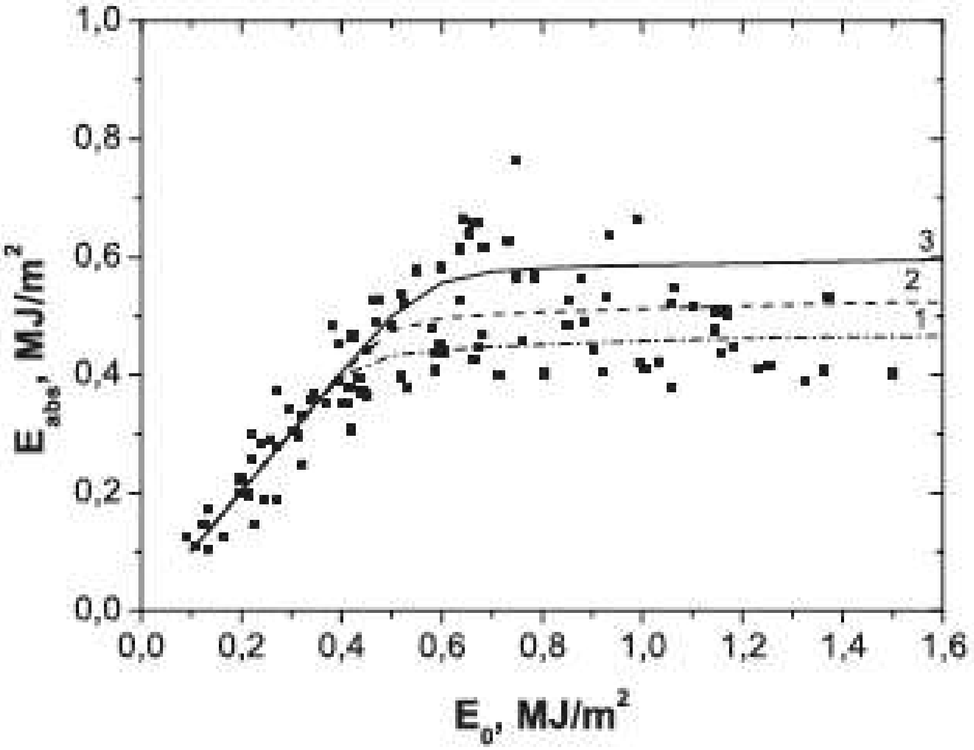


FIG. 2. The energy absorbed by the tungsten target over the energy stored in the incident plasma flow. Dots represent the experimental data obtained at MK-200 pulse plasma accelerator; curves represent the result of numerical calculations based on the second model. The first curve corresponds to $\dot{E}_{rad} = 10^{-8}$ W per evaporated particle; the second one corresponds to $\dot{E}_{rad} = 10^{-9}$ W; the third one corresponds to $\dot{E}_{rad} = 10^{-10}$ W.

E_{rad}/ptcl (W)

1: 10^{-8}

2: 10^{-9}

3: 10^{-10}

Differences on the required evaporation rate, not in the achievable power screening

Specific items for Li surfaces.

1) Sputtering
2) SEE
3) H- reflection

1) Alkali surfaces: 2/3 of sputter as ions

J.P. Allain, PhD Thesis

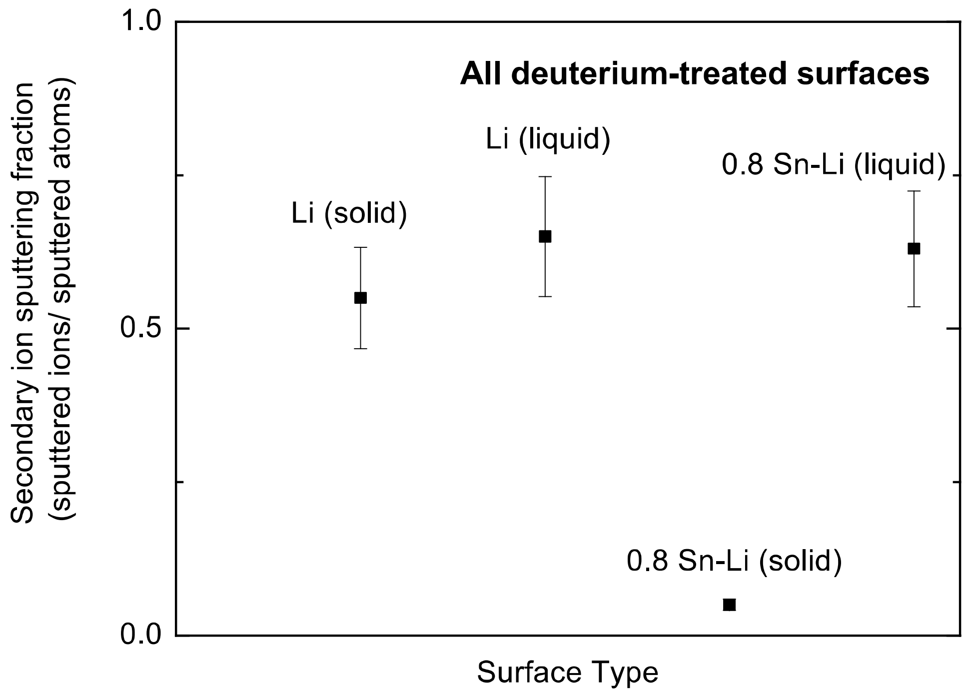


Figure 8.7. Secondary ion fraction of sputtered lithium atoms as a function of surface phase type for deuterium-treated surfaces.

2) SEE: Enhanced SEE observed in Li exposed to He, Ar and HGD plasmas

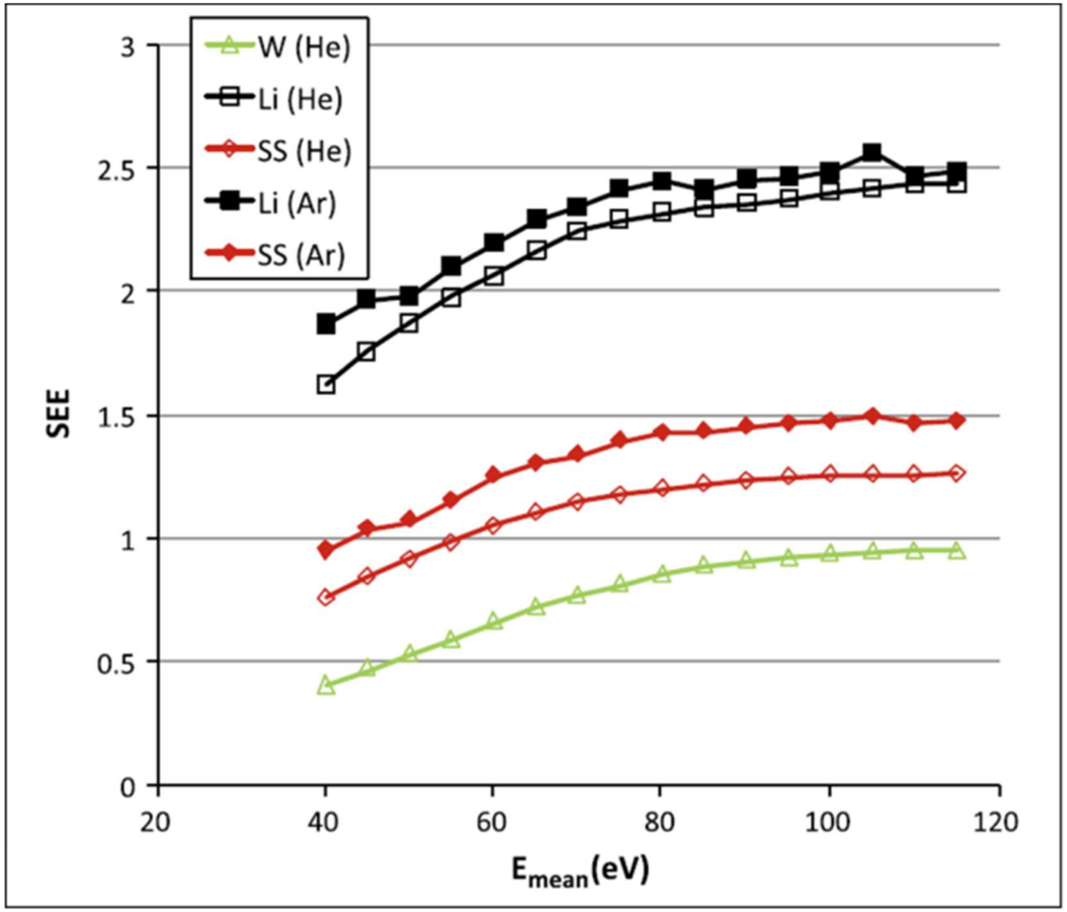


Figure 6: Results of the Li, SS and W SEE yields vs mean electron energy for He and Ar DC-GD [6]

Also seen in LiSn and in H plasmas

Effect of surface oxidation?

3) Reflection of negative ions

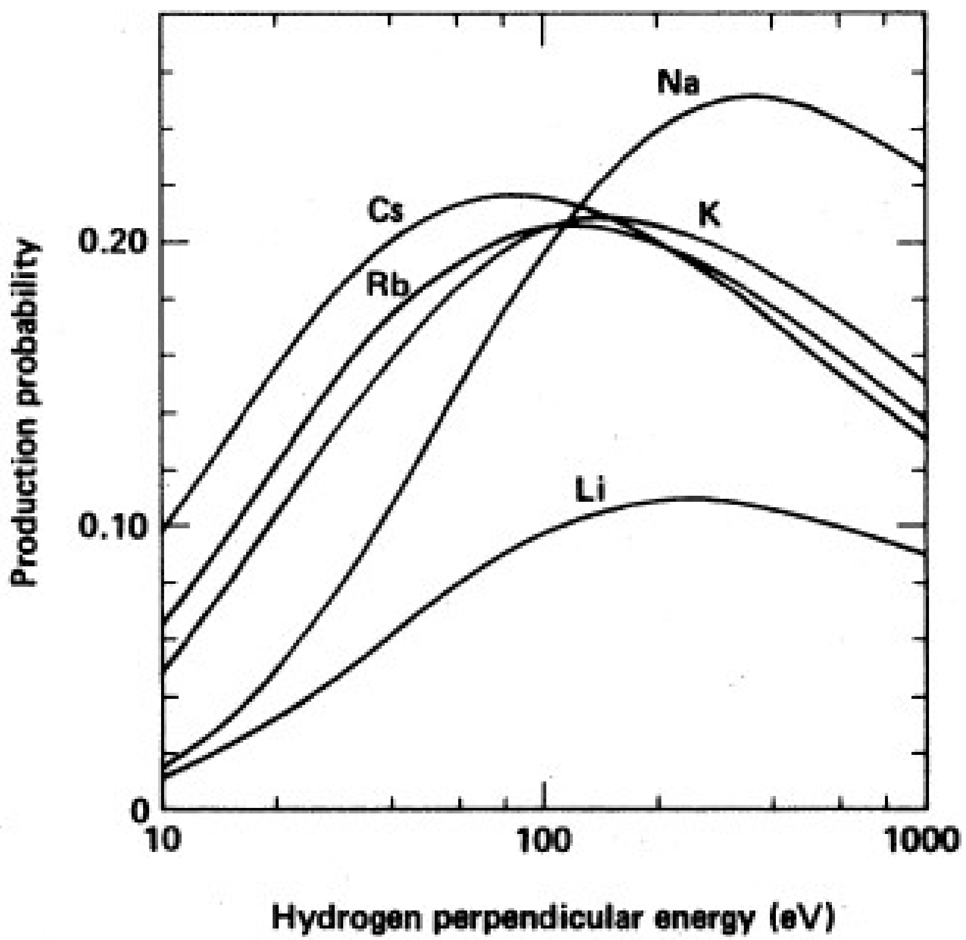


FIG. 7. The production probabilities for the different alkali metals plotted vs the perpendicular component of the hydrogen backscattered energy. For deuterium the energy scale must be doubled.

D^+

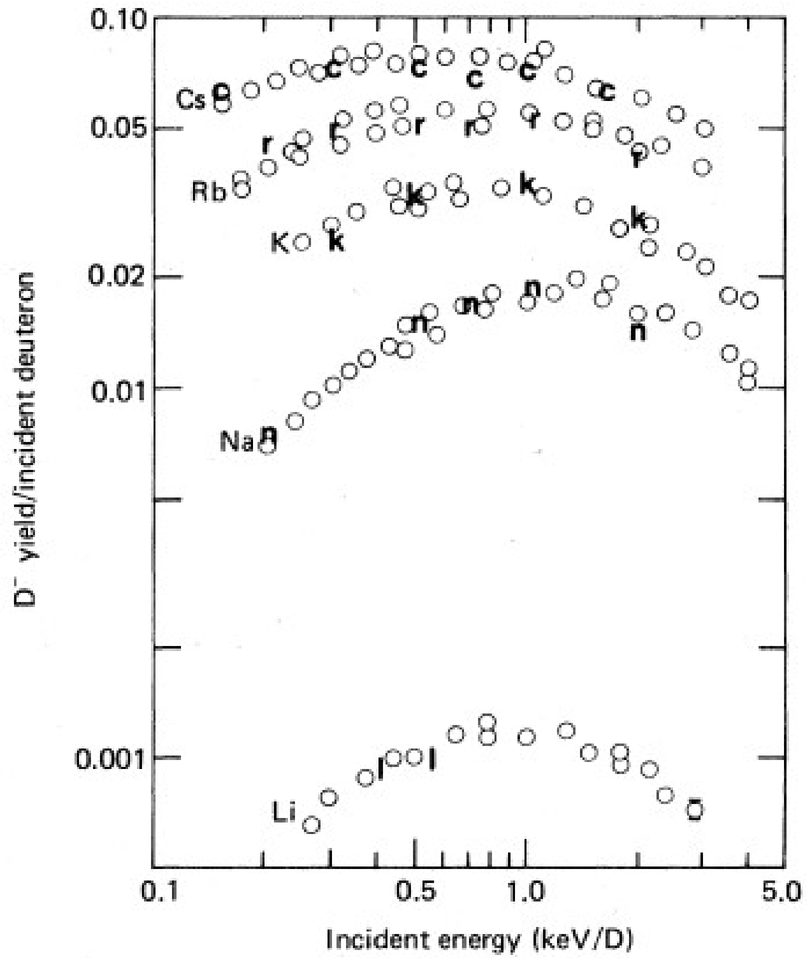


FIG. 5. Experimental NISEC values per deuteron for deuterium molecular ions incident normally upon the alkali metals vs the equivalent incident deuterium energy. The lower-case letters are the fits to the data using Eq. (7).

Isotope effect

Heavy particle processes

Interaction of H with Li vapour.

$H + Li \rightarrow Li^+ + H + e^-$

$\rightarrow Li^+ + H^-$

$H^+ + Li \rightarrow Li^+ + H$

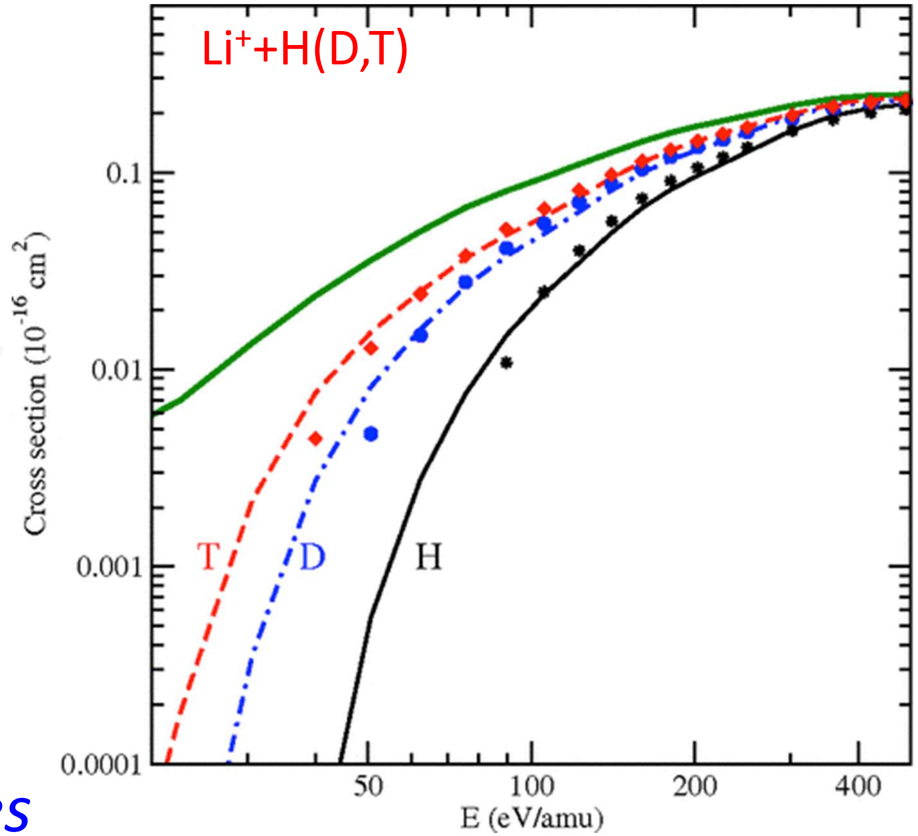
$\rightarrow Li^+ + H^+ + e^-$

$H + Li^+ \rightarrow H^+ + Li \ (Li^+ + e^-)$

$H^- + Li^+ \rightarrow H + Li$

$H \ (H^+) + Li_2^{\ (+)} \rightarrow prods$

Strong isotopic effect



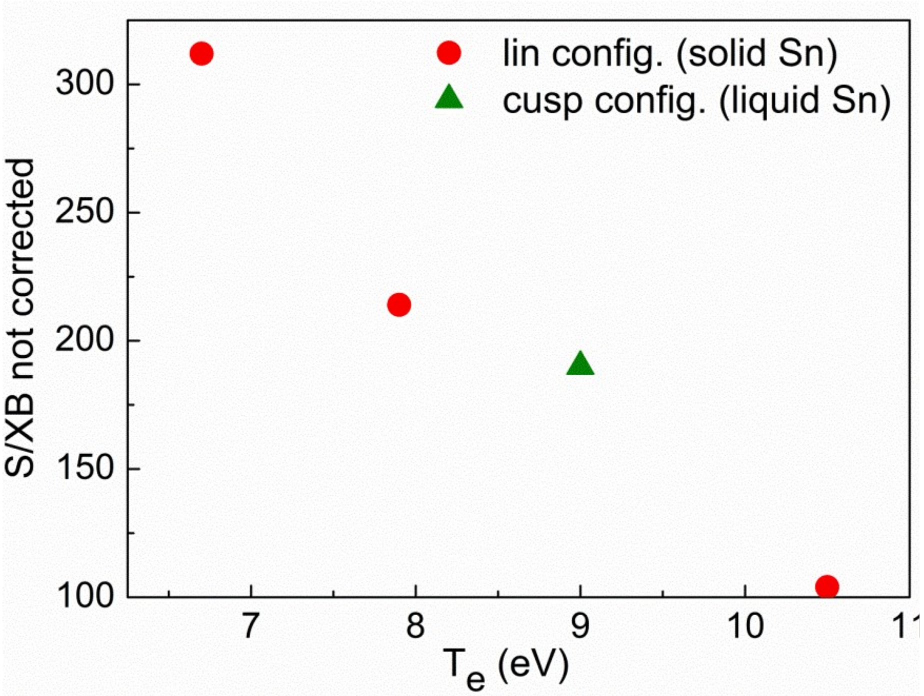
+ excitation/de-excitation processes

LF Errea et al, Physical Review A, 2008 - APS

Atomic data for fusion. Volume 1: Collisions of H, H_2, He and Li atoms and ions with atoms and molecules.
Barnett, Clarence F.et al.July 1990 Bibcode: 1990STIN...9113238B

BUT: Sn AM database: ???

SnI at 380 nm



Vasallo et al. 2017

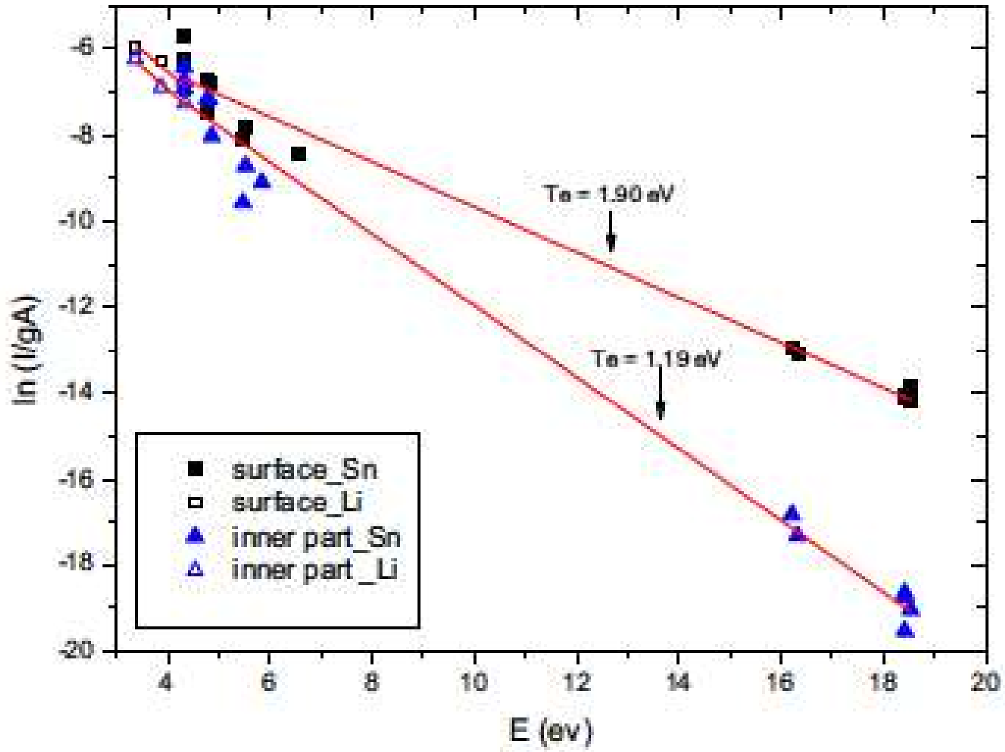


Fig. 3. The Saha-Boltzmann plot for the first laser shot of LIBS analysis. The black squares represent results from the surface of the sample and the blue squares represent the inner part of the sample (mechanically broken sample).

From LIBS experiments

M. Suchoňová et al. / Fusion Engineering and Design xxx (2016)

Rational for VS experiments

- Calorimetry: net heat to the target
- Power screened/ evaporation rate at the measured Tw

→ W/prtcle+ plasma parameters

→ CR Model!!

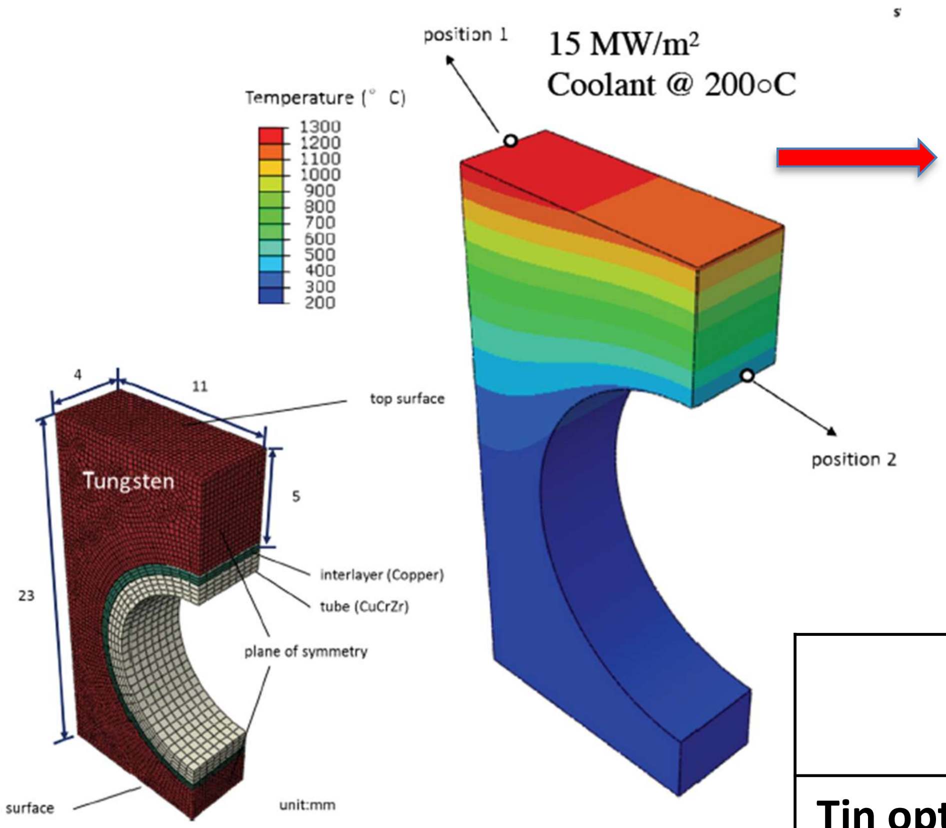
- Check for consistency: redeposition
- Add AM processes
- Recheck→ Design direct proof test.
- Change LM, power, etc…

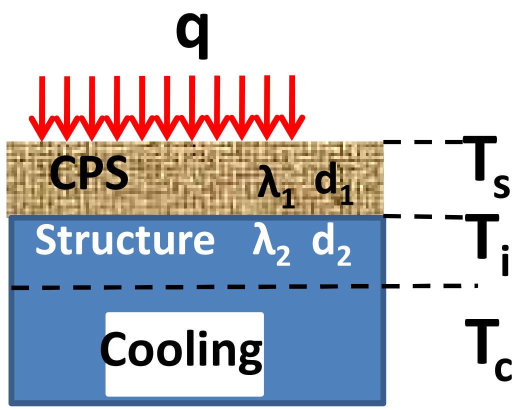
  - What the accumulated errors would be?

Rational for VS experiments

THANK YOU!!

Power Exhaust Issues



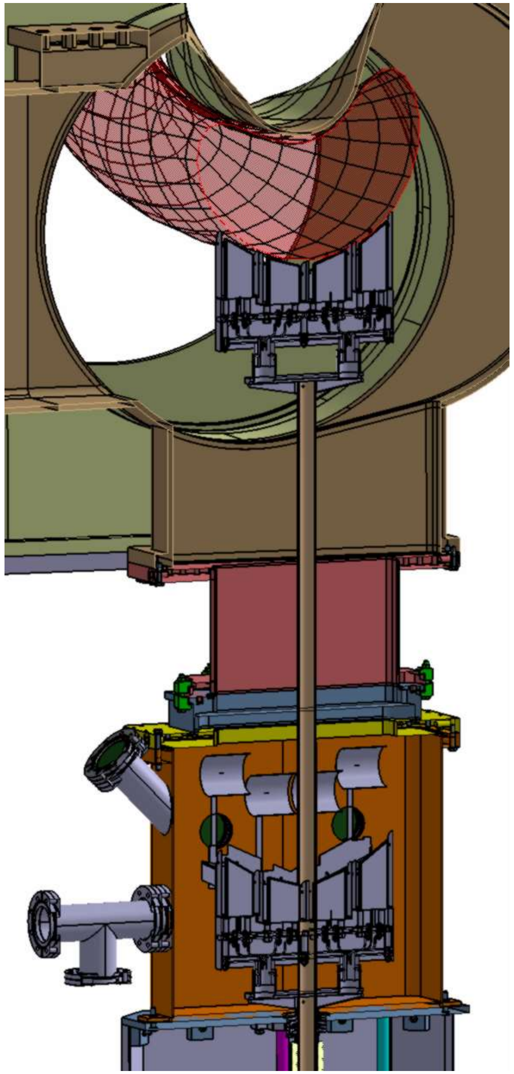


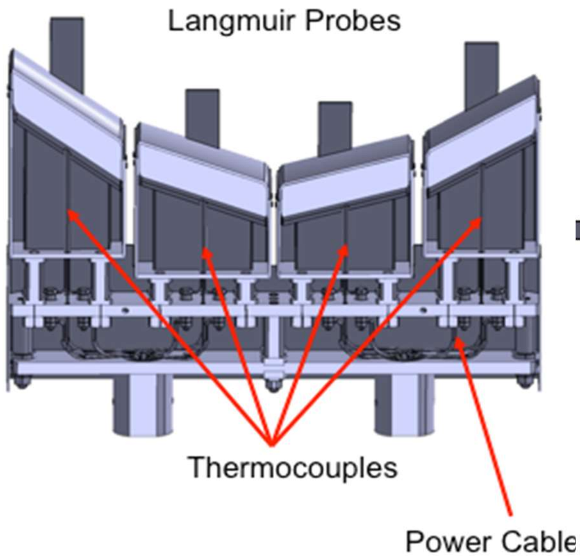
	Ts (°(T_w=150) 1% FLUX	d_1(mm) (CPS)	d_2(mm) (struc)	P (MW/m²)
Tin optim.	1277	1	3	28.75
Li optim.	480	1	3	8.25

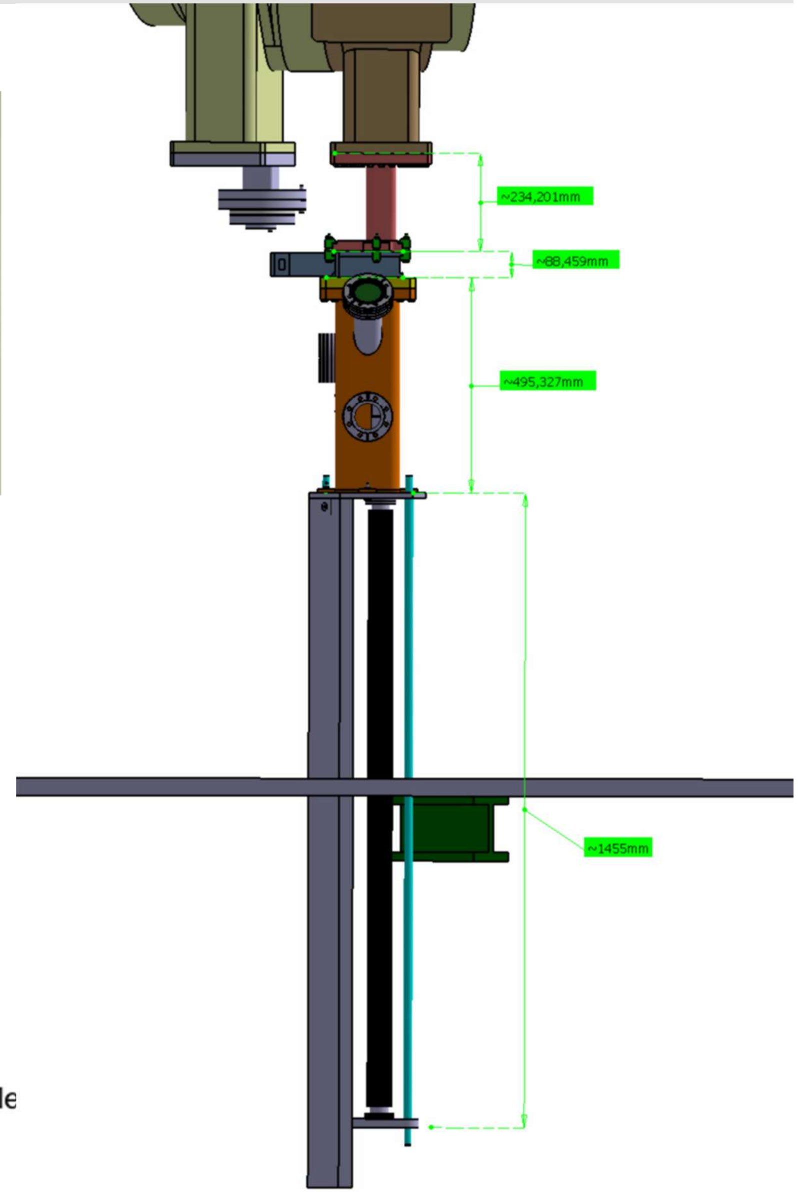
Coenen et al Phys. Scripta 2014

But: Thermal conductivity CPS+Li?: optimize structure
Maximum T Li?: Redeposition efficiency + T retention

LLL in TJ-II







- Two LLL installed in TJ-II (heated, movable, diagnosed)
- Spare manipulator system,1 m drive, motorized
- To be recycled (adapted) for OLMAT LM target positioning

Resources not available

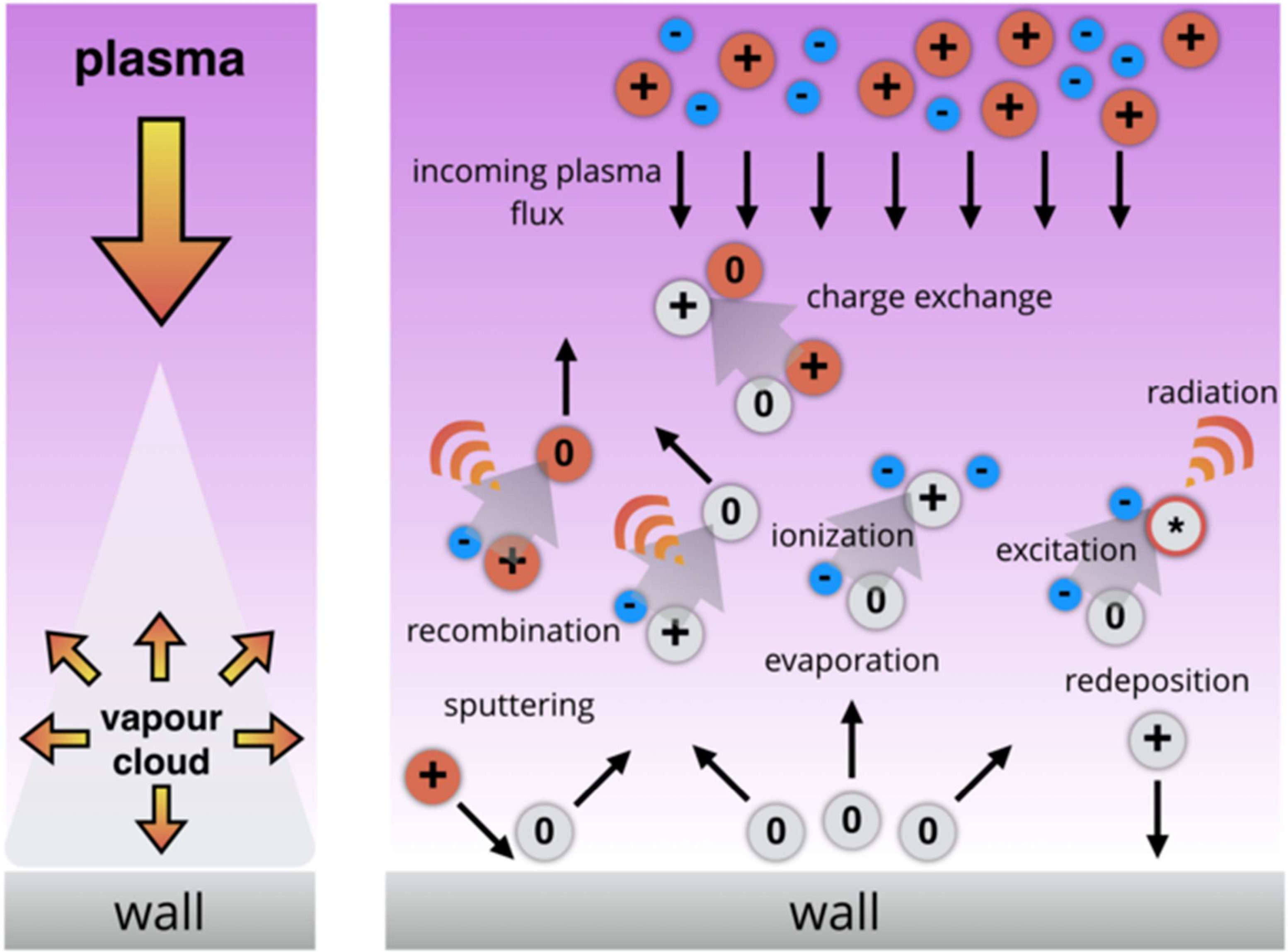
Laser System: ELM simulation+ CW heating if required

SPECIFICATION
YTTERBIUM LASER SYSTEM
Model YLS-1500/15000-QCW-WC-Y14

1. Optical characteristics

N	Characteristics	Test conditions	Symbol	Min.	Typ.	Max.	Unit
1	Operation Mode				CW / pulsed		
2	Polarization				Random		
3	CW and Pulsed Maximal Average Output Power		P_{nom}	1500			W
4	Maximum Peak Power			15000			W
5	Pulse Duration			0.2		10	msec
6	Maximum Pulse Energy	Duty cycle 10 %, PRR = 10 Hz, Maximum power	E_{max}	150			J
7	Duty Cycle*	Pulsed mode				50*	%
8	Tuning Range of Output Power			10		100	%
9	Emission Wavelength	Maximum output power	λ	1068	1070	1072	nm
10	Emission Linewidth	Maximum output power	$\Delta\lambda$		5	7	nm
11	Switching ON/OFF Time	Maximum output power			100	150	µs
12	Maximum Modulation Frequency	CW & Pulsed modes		2000			Hz
13	Output Power Instability	Maximum output power 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 15000W, 15% for 10000 W,……., 50% for 3000W and lower*



For Li add:

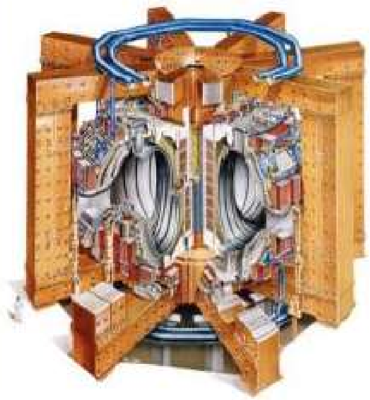
- *Anomalous enhanced SEE*
- *Reflection of neg. ions, H^-*
- *Sputtering as Li^+*

Complex AM & Plasma Physics!!

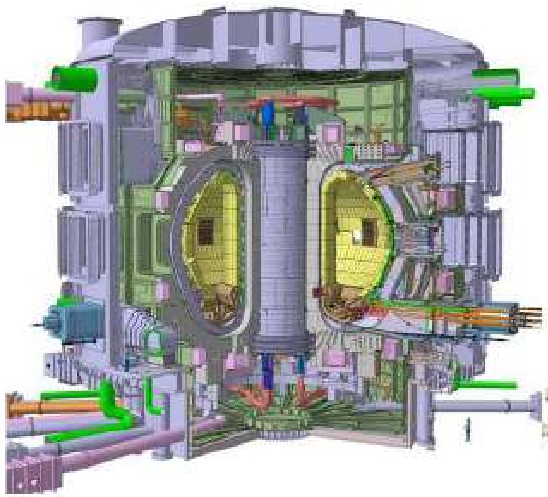
Evolution of Fusion Devices

Magnetic confinement seems to be the most successful approach to fusion.

Tokamaks have achieved the best parameters so far.

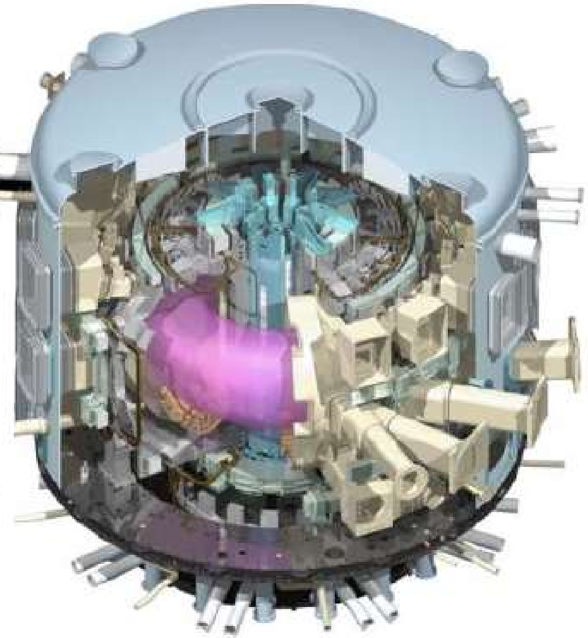


JET
(Current)
Participants: EU
<u>*Heat*: 16 MW</u>
Plasma: 80 m^3



ITER
(2025)
Participants: EU, Japan, USA, Russia, China, S. Korea, India
<u>*Heat*: 500 MW</u>
Plasma: 840 m^3

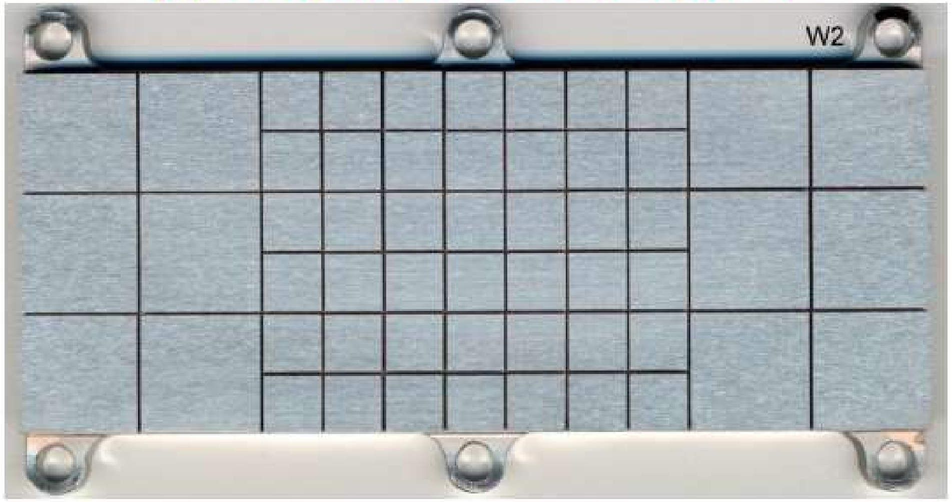
DEMO
(2040-50)
Participants: EU
<u>*Heat*: 2000-3000 MW</u>
Plasma: 2200-2300 m^3

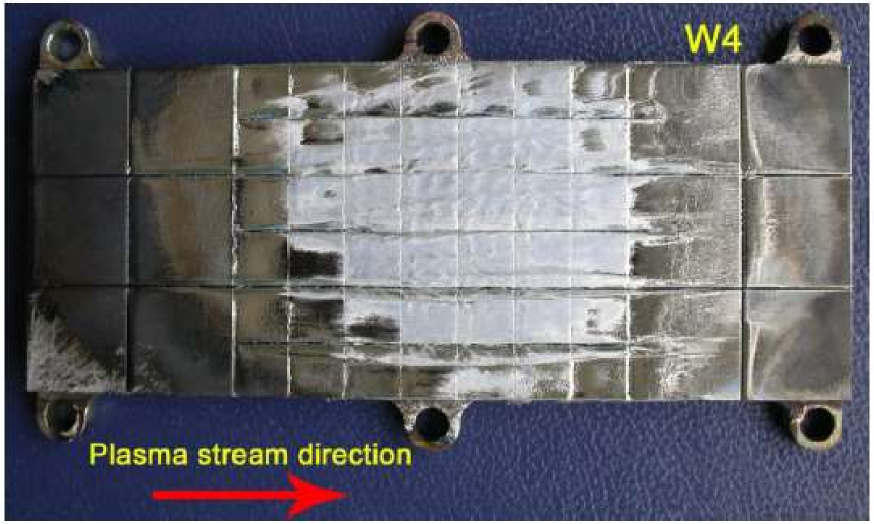


Power density to the target continuously increasing!!

Material Challenge

[2] Tungsten. Melts at ~3600 K





ELMs have to be reduced and disruption suppressed at all costs.

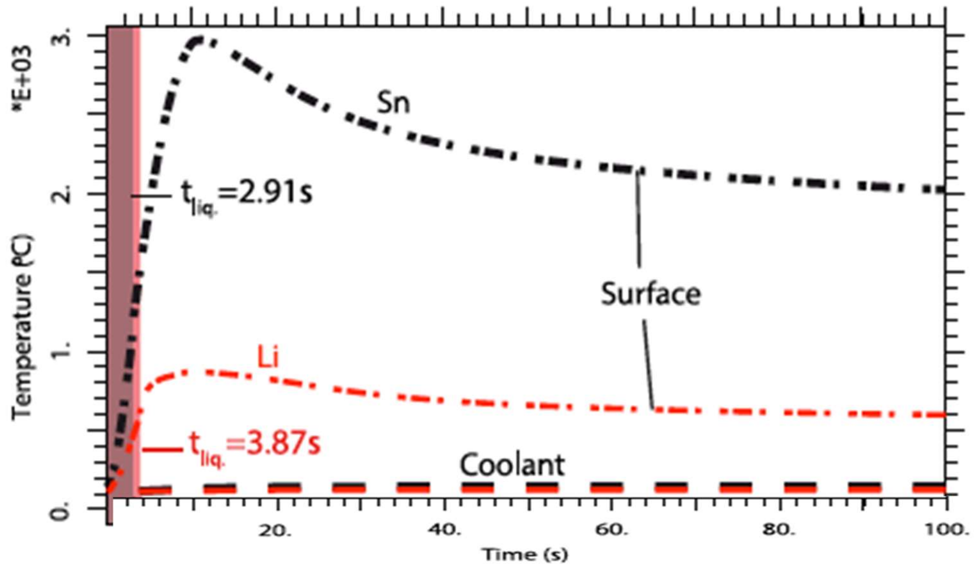
Even if we achieved this, *solid materials will likely melt.*

Several activities oriented to make W (composites) DEMO compatible… (see i.e., G. Dinescu…)

Limitations (some)

✓ Lack of actual Divertor plasma scenarios. Need of modelling. Restricted to comparative studies of LM, CPS, closed loop… in some instances.

✓ Limited pulse duration (time for SS Temp 2-5s)



Raclette modeling

✓ Disruption power loads achievable only in a small area

✓ REAL DIVERTOR PLASMA EXPOSURE STILL MANDATORY