# Reactor Divertor designs based on Liquid Metal Concepts


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*On behalf of the ISLA International Committee



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# OUTLOOK

- Liquid Metals in Fusion. Brief review of concepts
  - Free Flow vs CPS proposals
  - Metal Selection
- "Traditional" showstoppers
- A conservative approach: regenerative, protecting coatings
- Issues towards an Integration Scenario
- Pending R&D activities

# Motivation

- *What do we need to know for the design of a Liquid Metal-based Fusion Reactor?*

*- What is the best LM in terms of:*

*- Heat and particle exhaust characteristics*

*- Plasma Compatibility*

*- Stability under magnetic fields and neutron irradiation*

*- Performance under transient events*

*- Safety issues: T retention, chemical reactivity, vacuum loss,..*

*- Compatibility with the rest of elements: integration issues*

*- Concept implementation: engineering challenges, replacement*

*- Price, availability*

*-....*

# Motivation 2

- *Which options do we know (have)?*

  - *LM: Li, Sn, Ga, Sn/Li,…*
  - *Concepts: Free flowing/ Static (CPS)*
  - *Cooling: Radiation-evaporation/Conduction/ LM circulation*
  - *FW options: LM-High Z*

*EuroFusion Activities: Li,Sn, Sn/Li+ CPS+ conduction+ ??*

# Background: From ITER to DEMO

**Table 1.** Overview of key parameters of the ITER ($Q = 10$) and DEMO1 reference designs (2013).

| | ITER ($Q = 10$) | DEMO1 |
|---|---|---|
| R[m] | 6.2 | 9.0 |
| A | 3.1 | 3.6 |
| $\kappa_x$ | 1.85 | 1.75 |
| $\delta_x$ | 0.48 | 0.50 |
| $B_T$ (T) | 5.3 | 6.5 |
| $I_P$ (MA) | 15.0 | 16.8 |
| $P_{fus}$ (MW) | 500 | 1790 |
| $P_{heat,add}$ (MW) | 50 | 50 |
| $\langle n_e \rangle (10^{19}\ m^{-3})$ | 10.1 | 9.3 |
| $n_{GW} (10^{19}\ m^{-3})$ | 11.9 | 8.6 |
| $\beta_{N,tot}$ | 1.8 | 2.5 |
| Pulse length (h) | 0.1 | 1.7 |
| $q_{neutron,wall} (MW\ m^{-2})$ | ~0.5 | 1.1 |
| Total dpa | ~3 | 20 + 30 |

| geometry parameters | SlimCS (2008) | ITER |
|---|---|---|
| leg length, $L_{sp}$ (in/out) | 1.37/**1.83m** | 0.97/**1.14m** |
| incl. angle, $\theta_{sp}$ (in/out) | 21°/**18°** | 38°/**25°** |
| Dome top below Xp | ~0.5m | ~0.55m* |
| V-shaped corner | **out** ** | in & **out** |
| Flux expansion(in)/(out) | 7/**3** | 7/**6** |
| Wet area for $\lambda_q^{mid}$ = 5mm (in/out) | 2.2/**1.9m²** | 1.4/**1.9m²** |

R P Wenninger et al. Nucl. Fusion **54** (2014) 114003

For DEMO: always the same wetted area at divertor target ($l_q$ scaling) but $P_{Div}$x3-4!
$Q_{neutrons}$: dpa x30
$T_{pulse}$ >20x
T wall DEMO: 600-800 °C

# The problem of heat exhaust

- **W** is material of choice for **ITER** divertor and sustains steady state heat handling of **5-10 MW m$^{-2}$**
- Power entering SOL in DEMO predicted to be higher by factor 6-9[1]
- → Alternative divertor materials can provide better overall performance?

[1]Maisonnier D, Cook I, Pierre S et al. 2006 Fus. Eng. Des. 81 1123-1130

**Solid metals: Surface driven degradation**


**Bulk effects: DBT+ neutron irradiation**

# Liquid Metals?

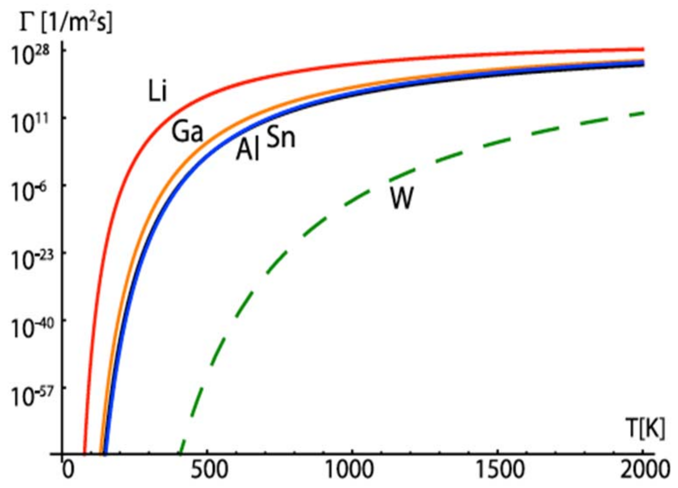
•First proposed for IFC Reactors
•Highly developed concept for USA MCF Reactors: APEX (Abdu et al. Fus Eng Des 2001)

- Powerful tool for protection of solid surfaces
- Possibility of continuous *in situ* surface renewal

## Traditional showstoppers:

+Excessive Pvap: plasma dilution, contamination
+T retention (Li)
+ LM worse than W in thermal conductivity
+ Splashing forces
+ Challenging Engineering

BUT:




(a) Higher Fluxes to the plasma

**Table 2.** Operational surface temperature limits based on evaporative flux.

| | $T_{min}$ (K) | $T_{max}$ (K) ($\Gamma_{Ev.}/\Gamma_{Pl} = 10^{-4}$) | $T_{max}$ (K) ($\Gamma_{Ev.}/\Gamma_{Pl} = 10^{-2}$) |
|---|---|---|---|
| Al | 933 | 1200 | 1450 |
| Ga | 303 | 1100 | 1300 |
| Sn | 506 | 1272 | 1528 |
| Li | 454 | 635 | 755 |

Coenen et al. Phys. Scr. **T159** (2014) 014037

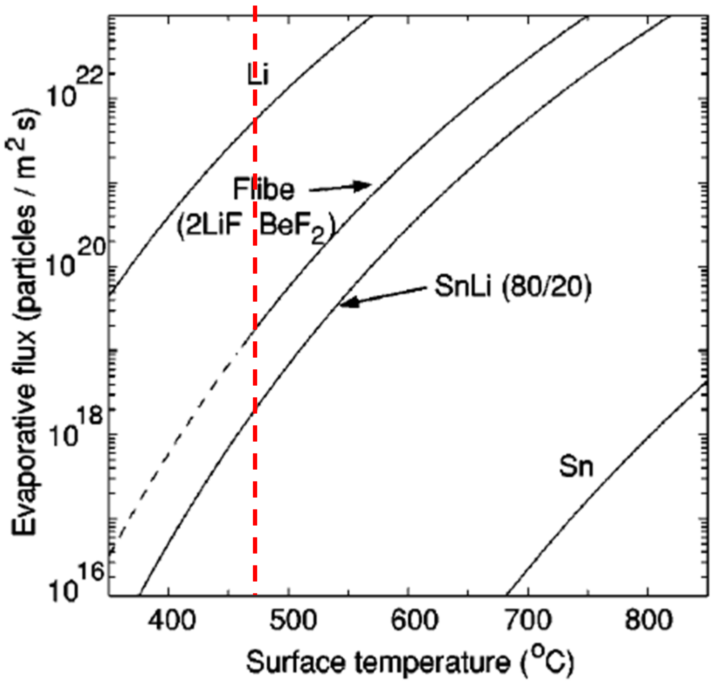
# Criteria for Selecting Liquid Metals

- No activation/transmutation by neutrons
- Strong surface tension
- Low vapor pressure
- Low (uncontrolled) H uptake
- Low Z preferred
- Material compatibility (corrosion, wetting…)

**Lithium, Tin, Gallium, Li/Sn alloys…**

| | Symbol (units) | Li | Sn | Ga |
|---|---|---|---|---|
| **Atomic number** | Z | 3 | 50 | 31 |
| **Atomic weight** | A | 6.94 | 118.7 | 69.72 |
| **Mass density** | $\rho$ ($10^3$ Kg/m$^3$) | 0.57 | 6.99 | 6.095 |
| **Melting point** | $T_m$ (ºC) | 180.5 | 231.9 | 29.8 |
| **Boiling point** | $T_b$ (ºC) | 1347 | 2270 | 2403 |
| **Surface tension** | $\sigma$ (Nw/m) at $T_m$ | 0.4 | 0.55 | 0.69 |
| **Dynamic viscosity** | $\eta$ ($10^{-3}$ Pa.s) at $T_m$ | 0.25 | 1.85 | 0.95 |
| **Latent Heat of vaporization** | $\Delta H_{vap}$ (kJ/mol) | 147 | 296 | 256.1 |
| **Thermal conductivity** | $\kappa$(W/m/K) at $T_m$ | 45 | 30 | 50.9 |
| **Molar Heat Capacity** | $C_m$ (J/mol/K) | 24.86 | 27.11 | 25.86 |

# The Li-Sn alloy    APEX choice!




Evaporation rates of four candidate liquid-wall materials.

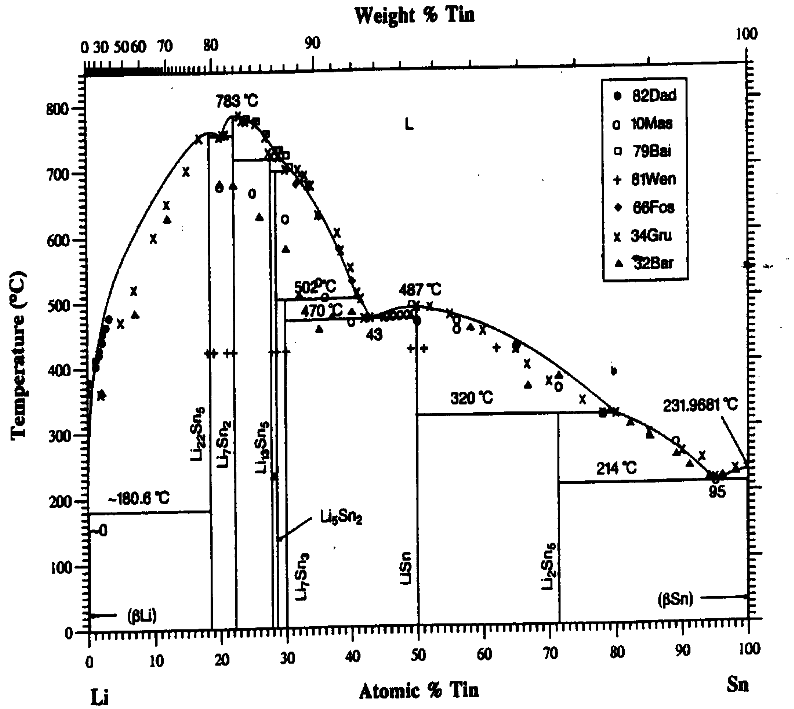



Figure 1.5. Equilibrium phase diagram of the Sn-Li system. For 0.8 Sn-Li sample the melting temperature is 320 °C as shown in the figure [26].

+ Low H retention (ISTTOK 2015)
+ Li surface segregation at MP (JP Allain,2000)

But: alloy. Phase transitions?

Li refilling at surface?

MP <350 ºC at Li/Sn<30%

# Material compatibility

From Liublinsky et al. ISLA 2013

## Li compatibility

| Material | Temperature, $^oC$ |
|---|---|
| HT-9 type steel | 800 |
| 316 type steel | 700 (no O, N) |
| V alloy | 1000 |
| Mo alloy | 1200 |
| W alloy | 1500 |

**From reference data Ga and Sn has the appropriate compatibility only with Be, W, Ta, Re and its alloys at the temperature up to 300-600$^oC$.**

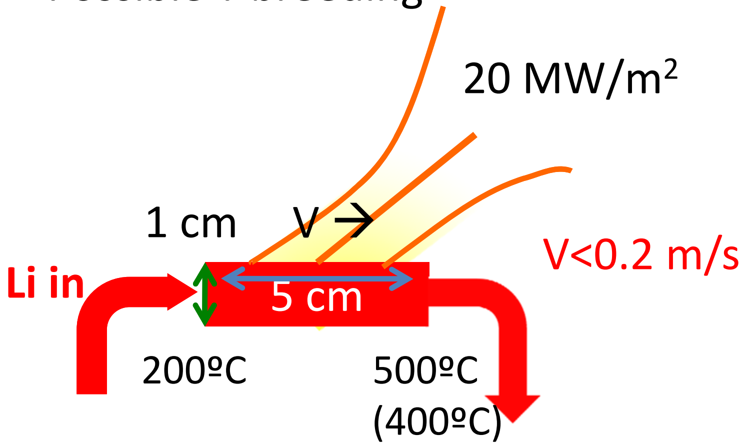
**Stainless steels (Fe-9Cr, Fe-18Cr-10Ni type) are not compatible at the temperature > 400$^oC$.**

# Flowing vs Static concepts 1

## Flowing

PROS:

- Active removal of particles and Heat loads
- Protection of Divertor and FW
- Possible shielding vs fusion neutrons (thick layer)
- Possible T breeding




CONS:

- Splashing
- Need external recycling for T recovery
- Magnetic viscosity
- Flow instabilities

## CPS

PROS :

- Simplicity
- No splashing issues
- Flexible (choice of geometry, LM)
- Small quantities of LM
- Concept maturity

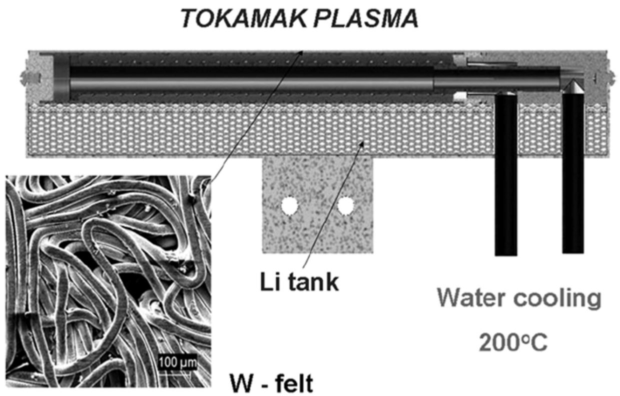
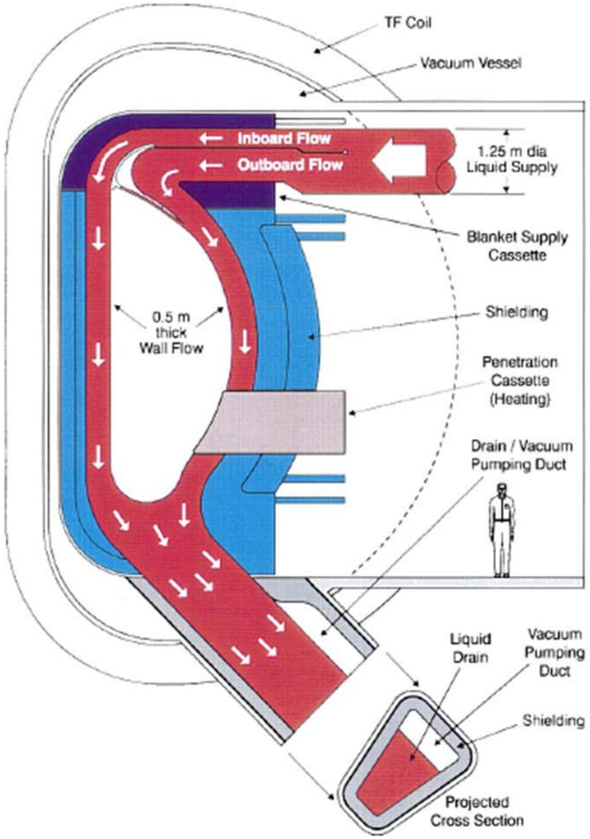



**Figure 7.** Schema of 'active' CPS Li element of steady-state 'W–Li' limiter (T-11M), Li tank/reservoir containing 30 g of Li.

CONS:

- Heat exhausted into the VV
- No particle pumping
- *Need of a solid support*

# Flowing vs Static concepts 2



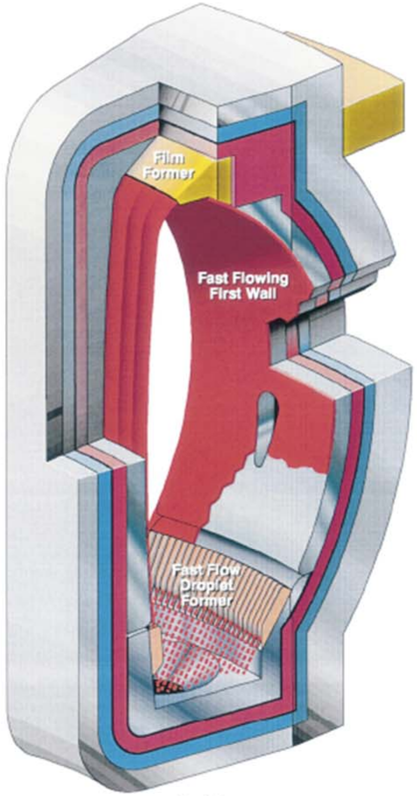




Fig. 24

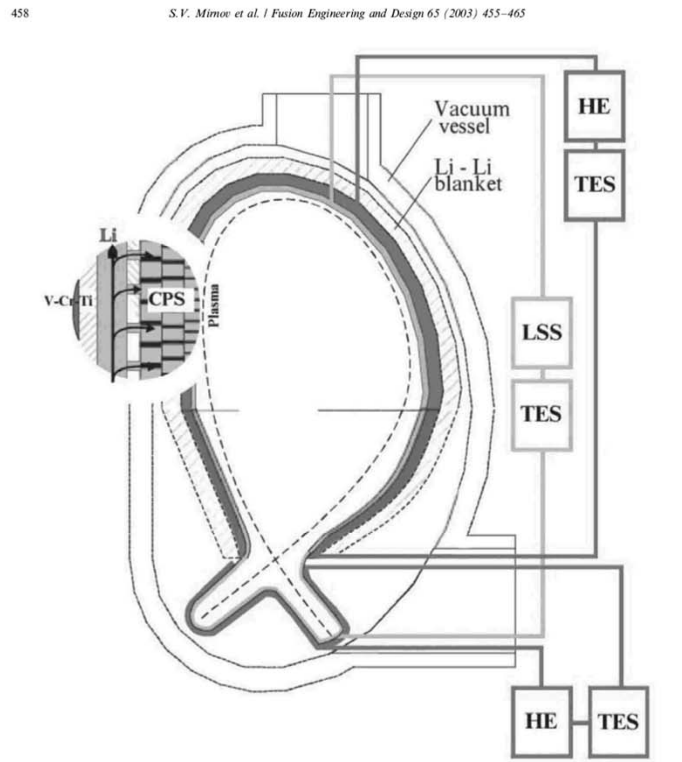



Fig. 2. Schematic view of fusion reactor with lithium divertor on CPS basis. HE, heat exchanger; TES, tritium extraction system; LSS, lithium supply system.

Thick FW blanket design:
ARIES-RS configuration
Provides neutron shielding
But: feasible???

The CLiFF FW concept
Lots of Li!!!

Design based on Capillary
Porous System (CPS)
Technical complexity?

# Heat Removal (Power Exhaust)

- Liquid Metal circulation
- Evaporation
- Plasma Radiation
- Conduction

Wetting problems!

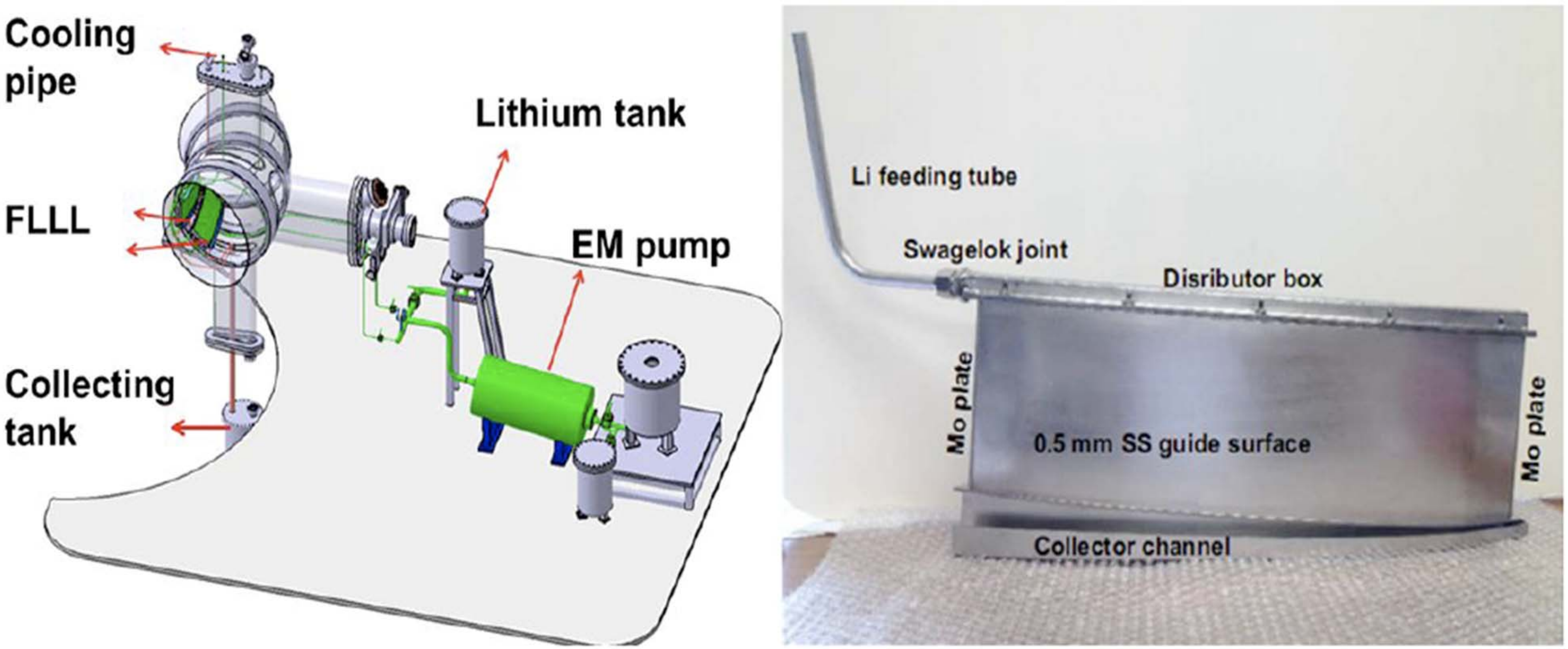



**Figure 2.** Flowing liquid lithium limiter system with the concept of thin flowing film in HT-7.

# LiMIT: Lithium/Metal infused trenches

**(D Ruzic et al NF 2011)**

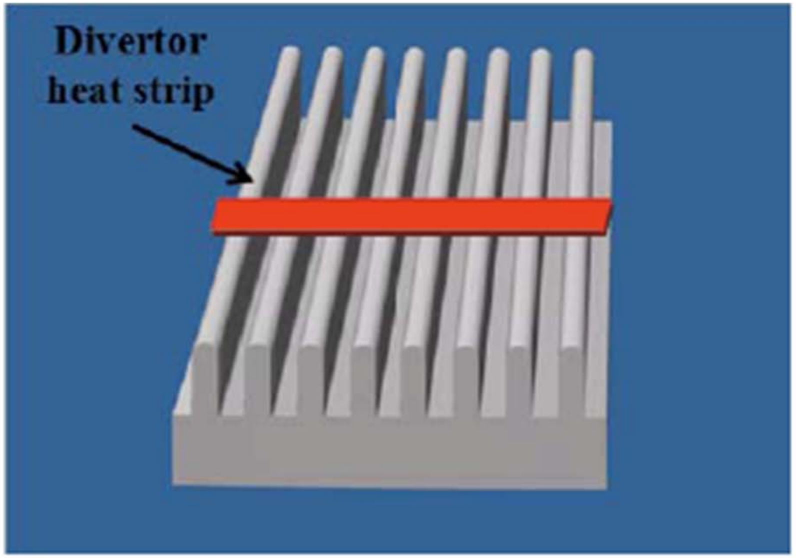



Figure 1: The LiMIT concept: Metal tiles with radial trenches containing lithium. The trenches run in the radial (poloidal) direction such that they lie primarily perpendicular to the toroidal magnetic field and the divertor heat stripe.

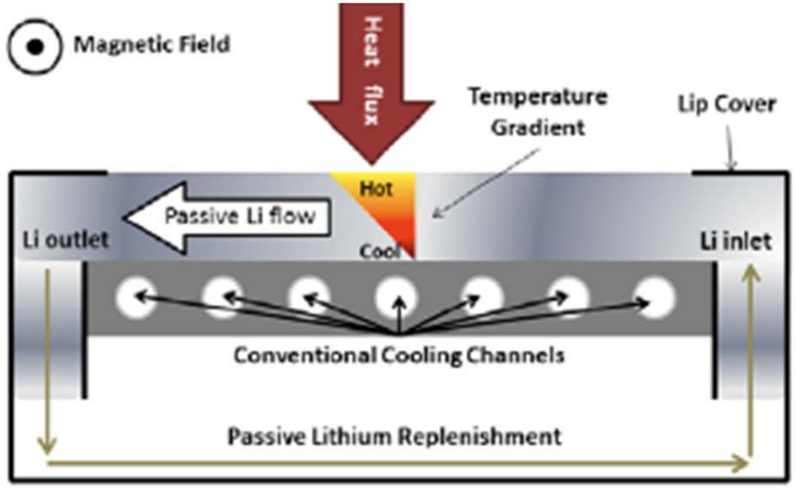



Figure 2: Concept for heat removal using TEMHD. The Li flows in the slots of the metal plate powered by the vertical temperature gradient.

Limited heat removal efficiency by MHD constrains

# Power Exhaust

- Flowing LMs: relatively moderate velocities required for SS heat loads. Concepts available. Li, LiFLi….

  But :Wetting issues, MHD-driven issues:

  Not  as mature as CPS concepts

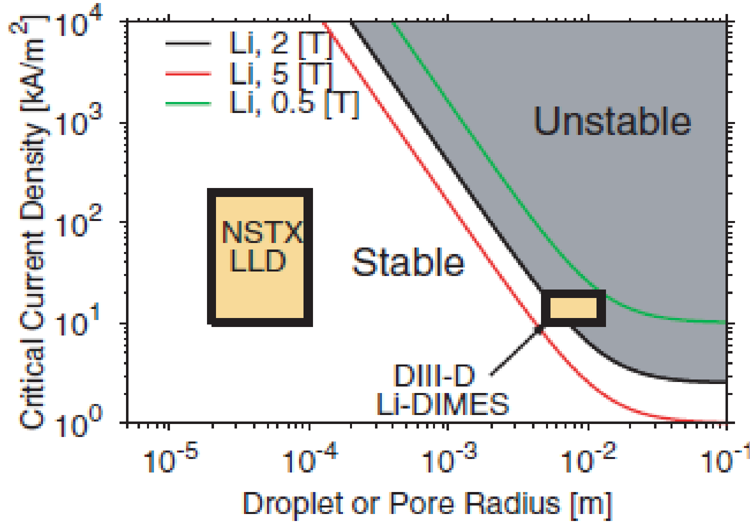
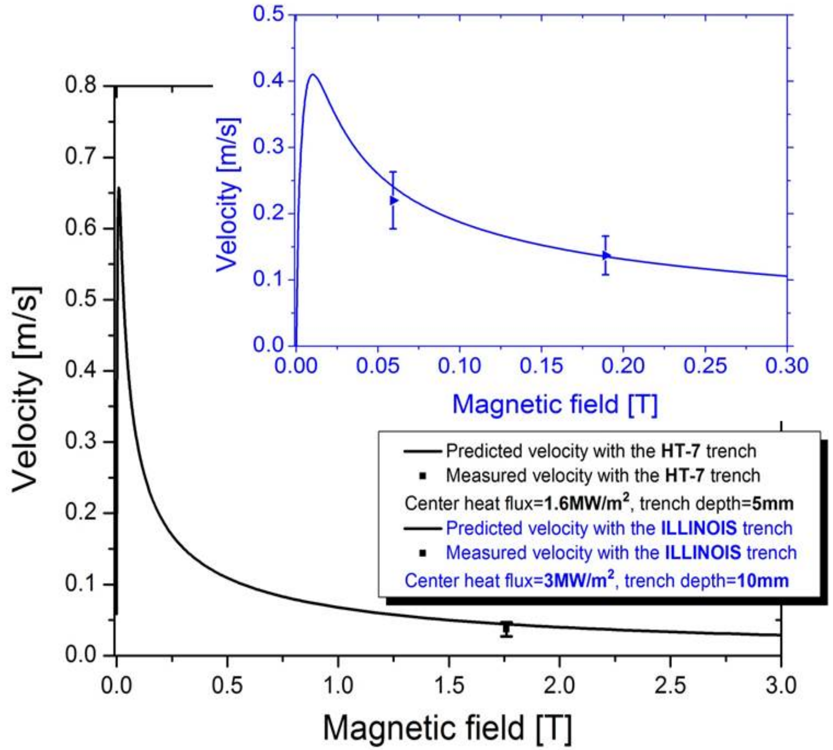
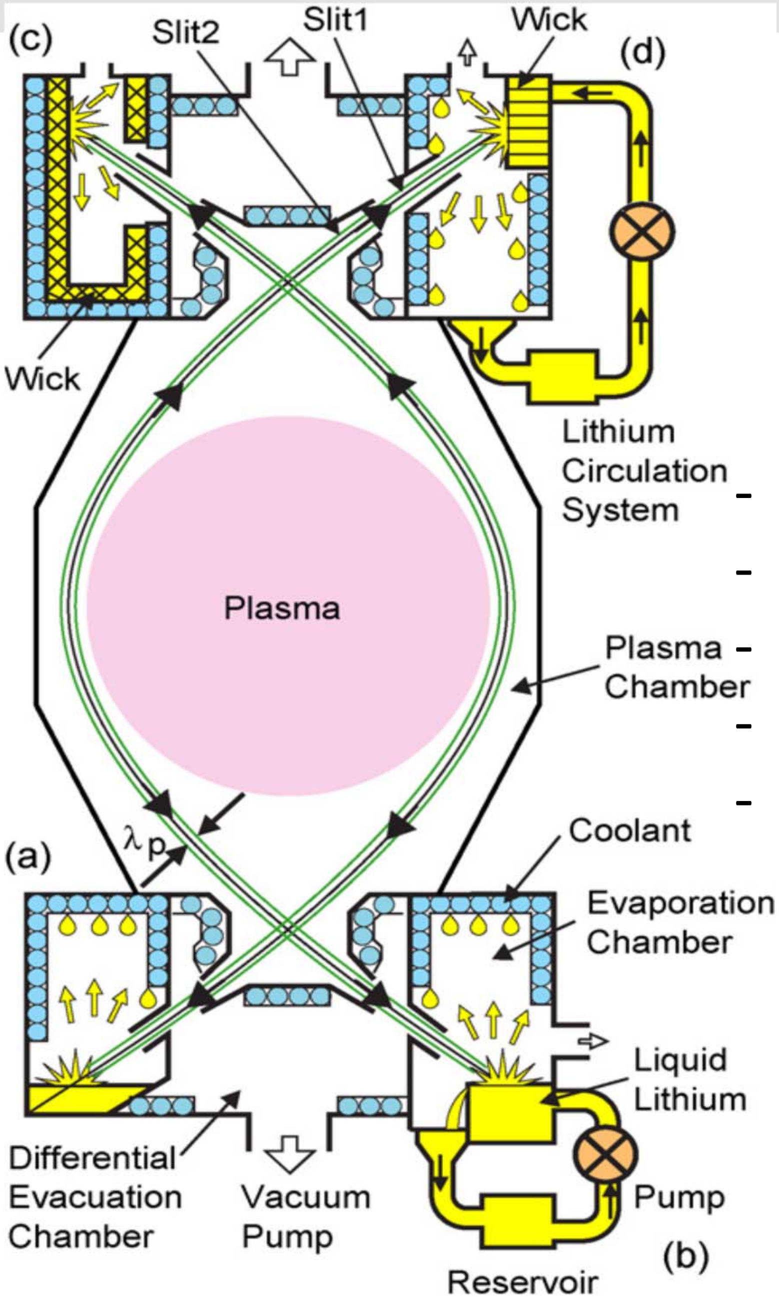



**Figure 7.** Stability diagram for a liquid metal under electroma body forces (with gravity and surface tension stabilizing). NS LLD operating space indicated ($B_T = 0.5$ T). Comparison wit Li-DIMES experimental space also shown ($B_T = 2$ T) [12]. N ejection events from the LLD were observed during the run campaign.



# Evaporation



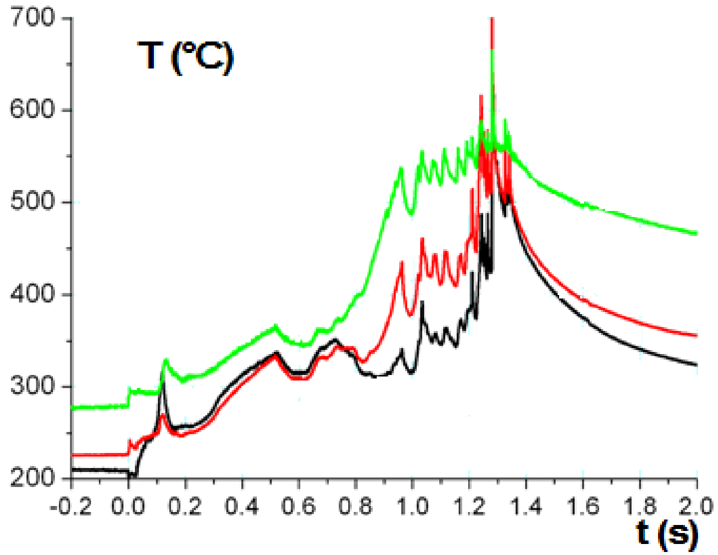

$\Delta H_{vap}$
Li: 147 kJ/mol
Sn: 296 kJ/mol

**Not effective under strong redepostion**

- Heat delivered out of the plasma
- Evaporation of 25 l/s required (Li)!
- Plasma formation on isolated chambers?
- Alignment issues
- First wall protection?

Nagayama, FED 2009

# Radiation cooling *(vapor shielding)*




FTU: Increase of Impinging Power leads to constant T at LLL: Vapor shielding effect

*Strong redeposition(>99%) of Li predicted and confirmed.*

*It leads to*

*- enhanced non coronal radiation*

*-loss of cooling by evaporation*

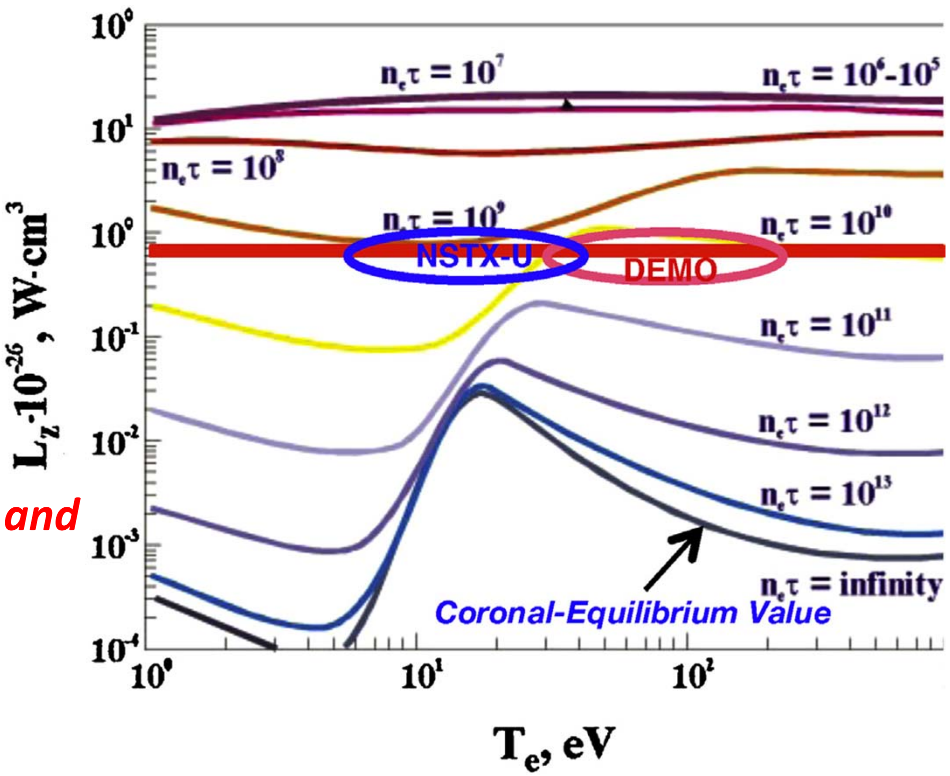
Low residence time por Li in plasma:

Non coronal radiative model:

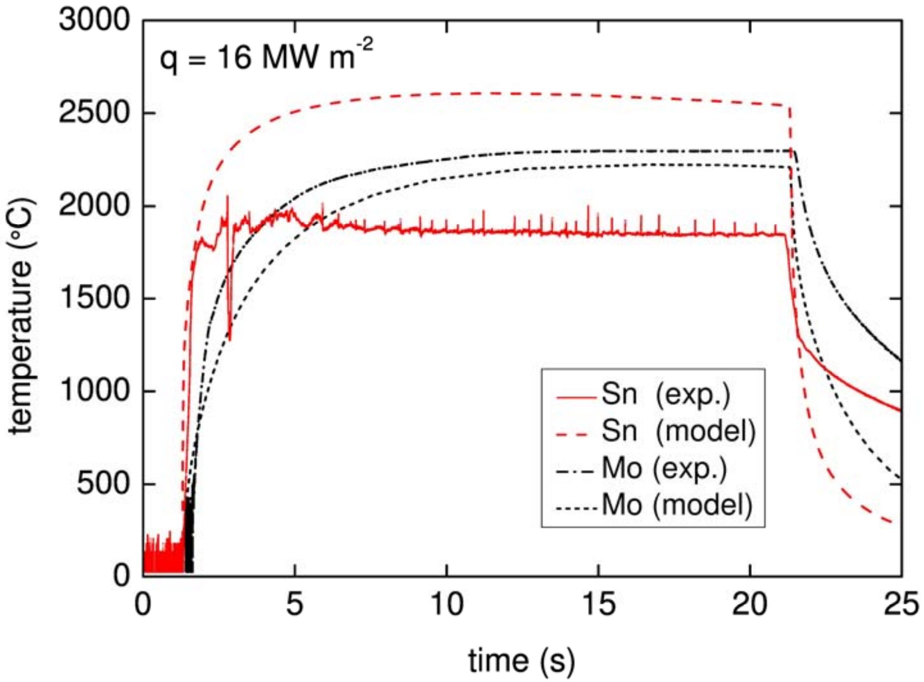
Enhanced radiation at the periphery

- Experimentally verified in some devices
- (FTU, T11-U, Magnum PSI,…)

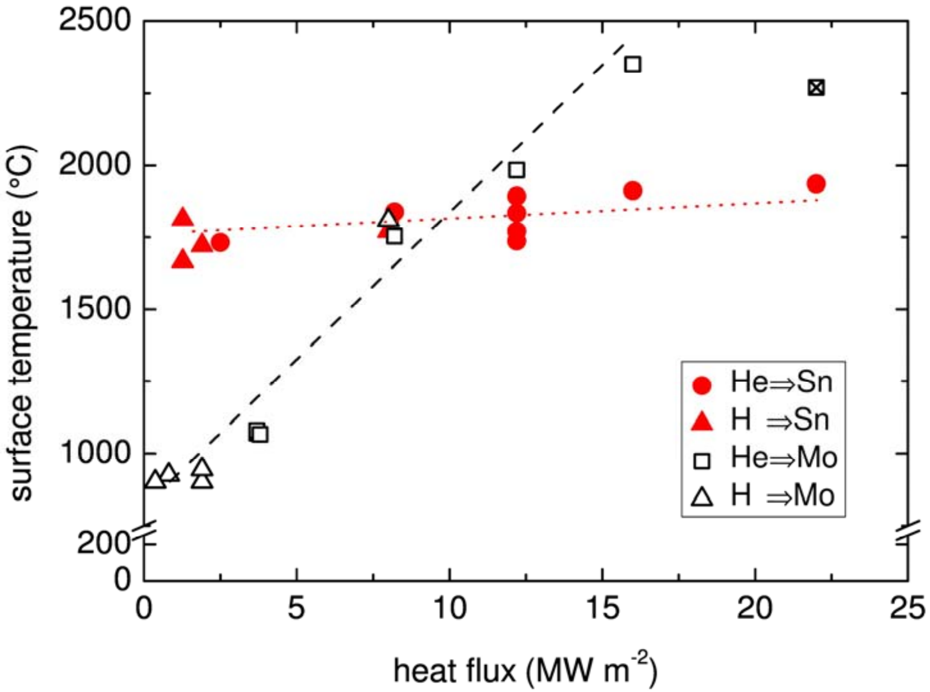
**700X higher than evaporation!**



## $T_{centre}$ evolution

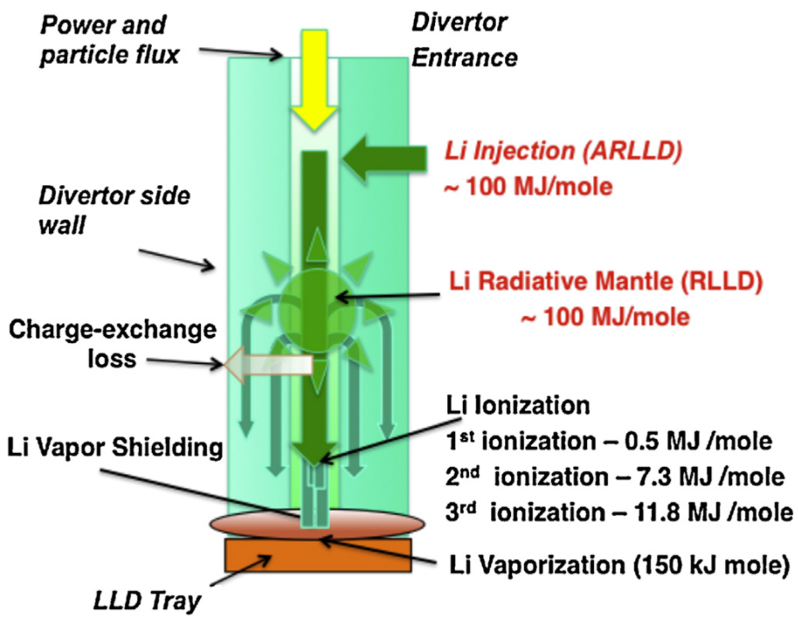



## $T_{centre}$ at end of discharge



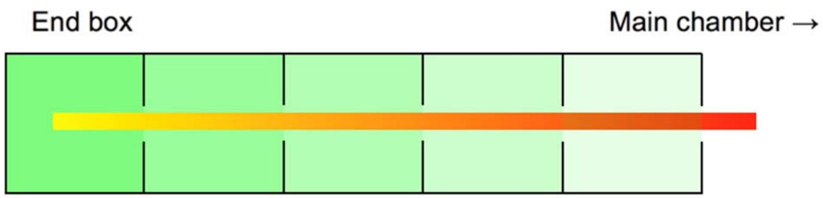

***Vapour shielding also seen for Sn in PILOT!!***

# The Radiative Liquid Lithium Divertor

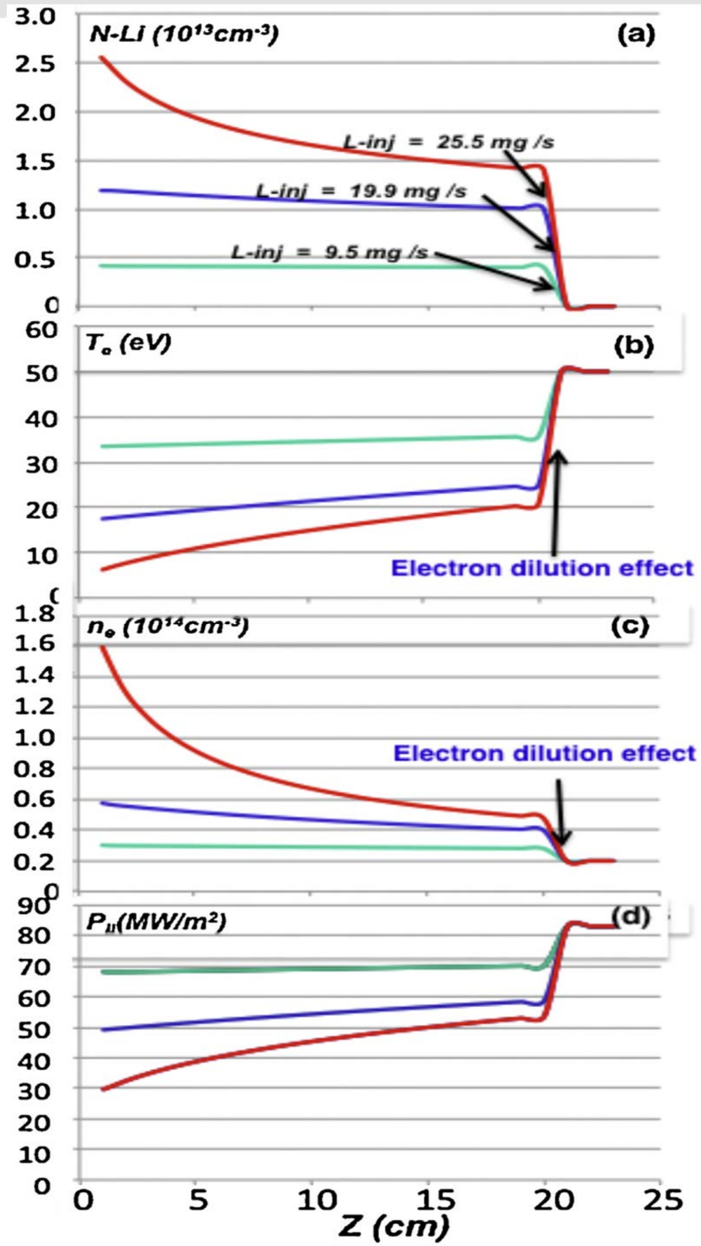



Ono et al : ARRLLD

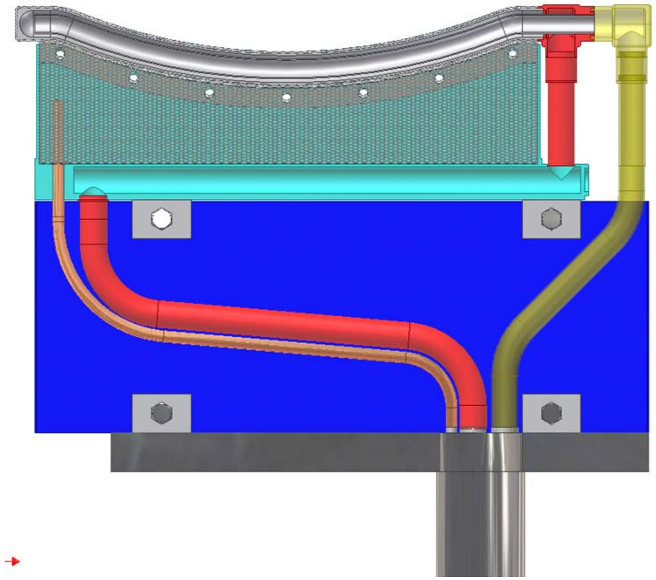
Goldston et al: Lithium box



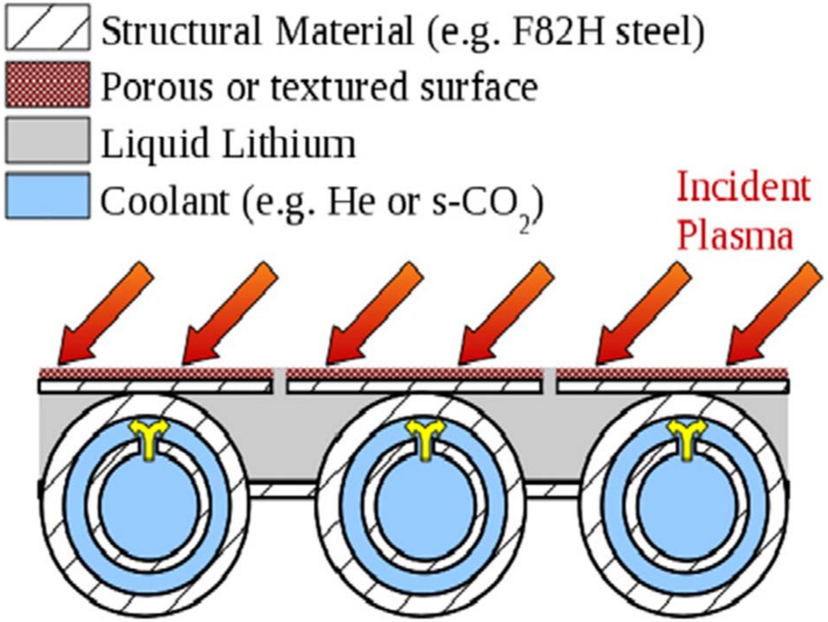

| T (wall) °C | 950 | 787.5 | 625 | 462.5 | 300 |
|---|---|---|---|---|---|



# Conduction: The CPS concept



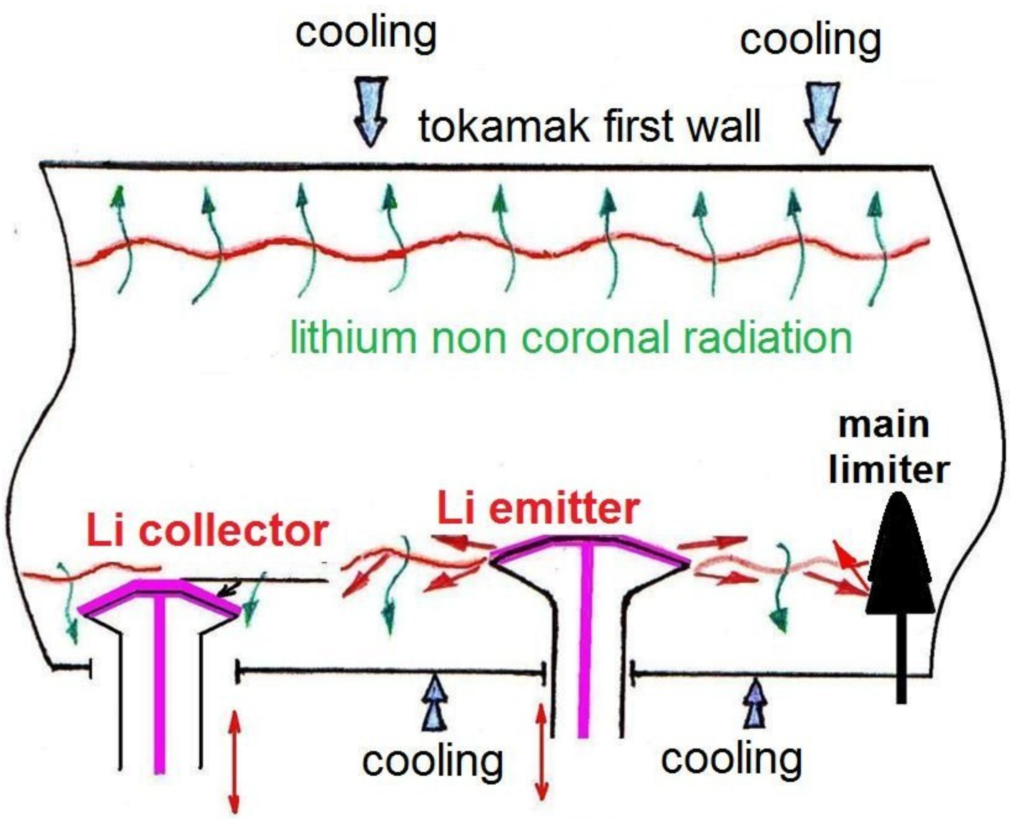
FTU Cooled Lithium LImiter




Schematic diagram of the actively-supplied, capillary-restrained systems with a T-tube

Porous systems used for holding LM in place by capillary forces (Evtikhin et al 1996)

# T11-M. S Mirnov et al.




"Badminton model"

Several identical Li-limiters in tokamak chamber can be used as emitters and collectors in turn by periodical change their relative mechanical position in SOL or by use of local magnetic perturbations

# T retention

At T< 400ºC: 1:1 uptake: LiH formation?

M.J. Baldwin *et al*

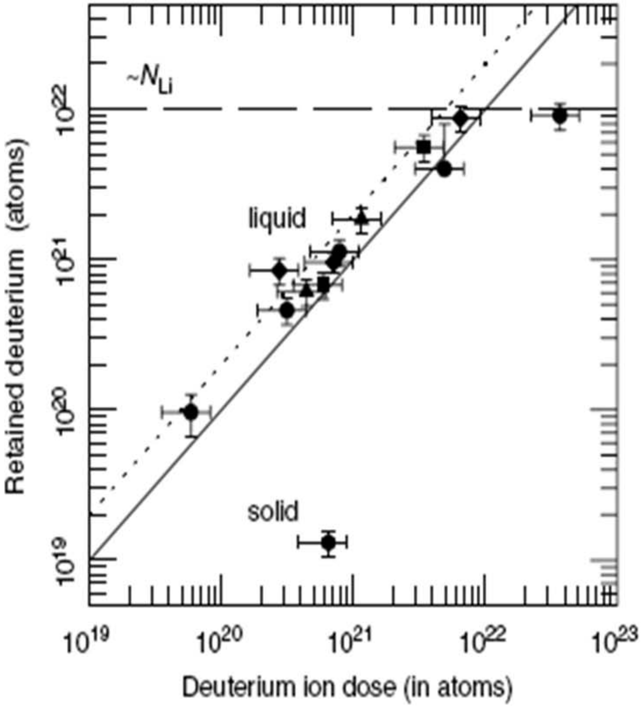
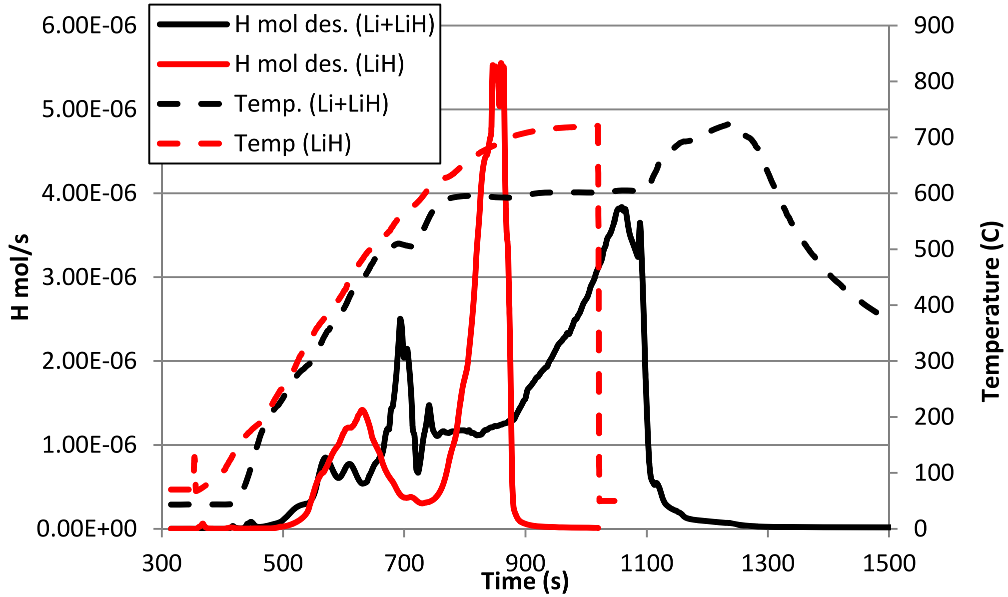



**Figure 5.** Plot of deuterium atom retention against plasma ion fluence. Data points are TDS measurements for lithium samples (liquid and solid) exposed to deuterium plasma. The sample exposure temperatures were: (solid) 323 K, (liquid) ● 523 K, ■ 573 K, ♦ 623 K, ▲ 673 K. The solid line indicates full retention of ions. The upper dashed line is the number of lithium atoms in samples. The dotted line is an estimate of the total atom fluence received by samples: the sum of the measured ion fluence and calculated neutral atom fluence [34].

Ciemat experiments (Oyarzabal et al)

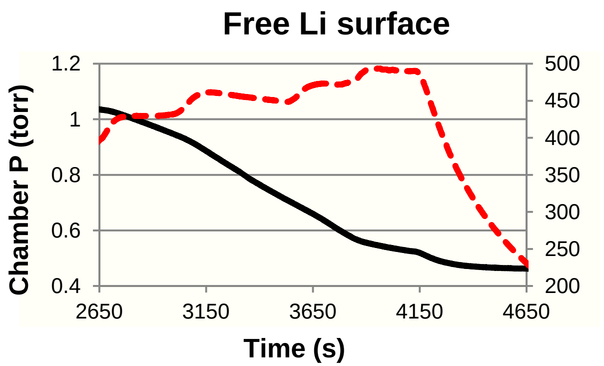


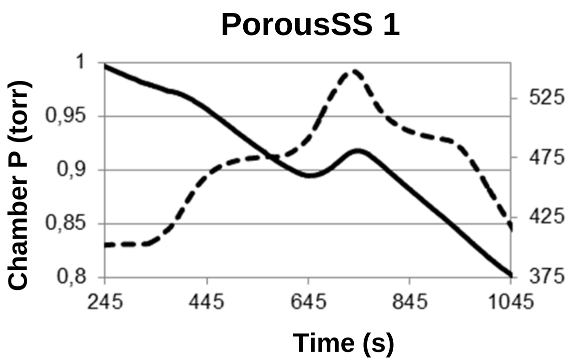

No “stable” LiH formation when in a hot Li matrix (T>400ºC)

- Preliminary PILOT PSI experiments confirm lack of retention through LiH formation at T> 460ºC

# T (H) RETENTION. POROUS SYSTEM & OPEN SURFACE

## HYDROGEN ABSORTION Vs TEMPERATURE



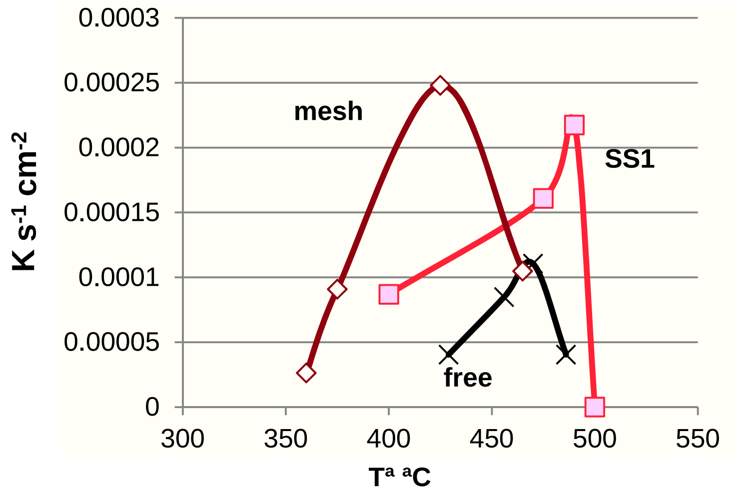

Uptake of $H_2$ by Li: The rate of absorption is increasing with temperature ( Ea~0.5 eV), but, at T~500ºC it vanishes!

- Agreement with TDS data
- For LLL CPS, no uptake at T~400ºC (capillary effect, plasma *vs* gas effect, oxygen contamination?)

**Absorption rate constant (K)**

$$\mathrm{Ln}\,\frac{P}{P_0} = -K\,t$$

K calculation deduced from de ln(P/Po) plot Vs time and divided for the exposed Li area




**Máximum value at 400-500ºC**

**Differences between samples: effect of the surface, temperature, contamination…**

For SSmesh, measurements at the same temperature at different $H_2$ concentration were performed:

Previous H absorption in Li does not affect the K value after the limit of solubility of the first phase (H concentration: 1-3% at these temperatures) has been reached.

# H DESORPTION. POROUS SYSTEM & OPEN SURFACE

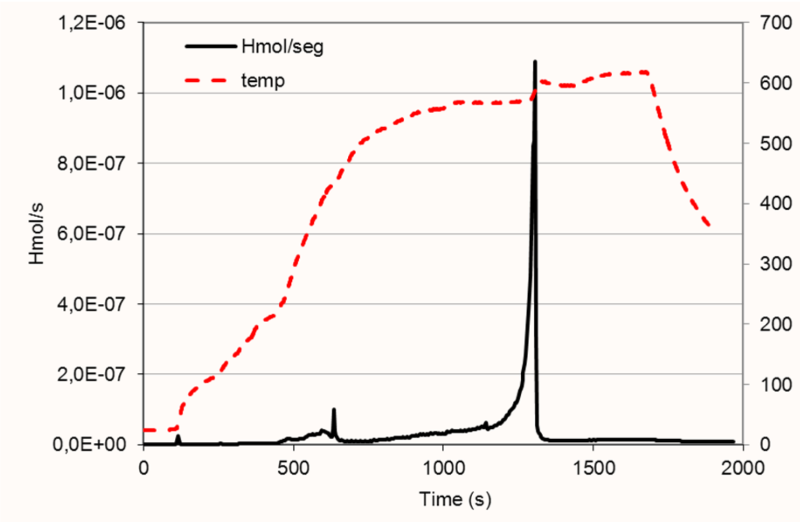
## THERMAL DESORPTION SPECTROSCOPY (TDS). H DESORPTION & Li EVAPORATION

**With TDS procedure 2 phenomena are taking place simultaneously: H desorption and Li evaporation.**

**At constant temperature (Kr=constant) $H_2$ desorption flux is proportional to the Hmol/Limol ratio squered ($C^2$):** $J = Kr * C^2$

### H desorption. Lithium in open surface

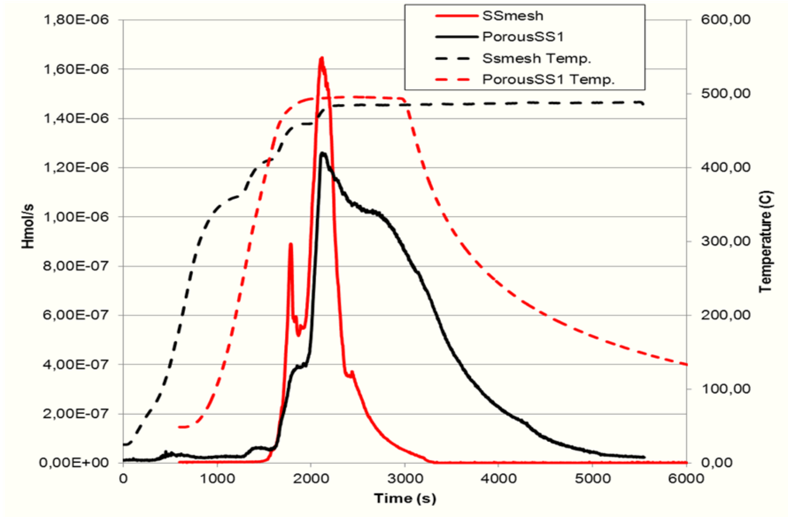
**At constant temperature H desorption increase with time**




**Li mol evaporation > H mol desorbed and very few H mol can be desorbed before Li is completely evaporated**

### H desorption. Lithium in porous system

**At constant temperature H desorption decrease with time**




**Li mol evaporation < H mol desorbed and most of H can be desorbed before Li is completely evaporated**

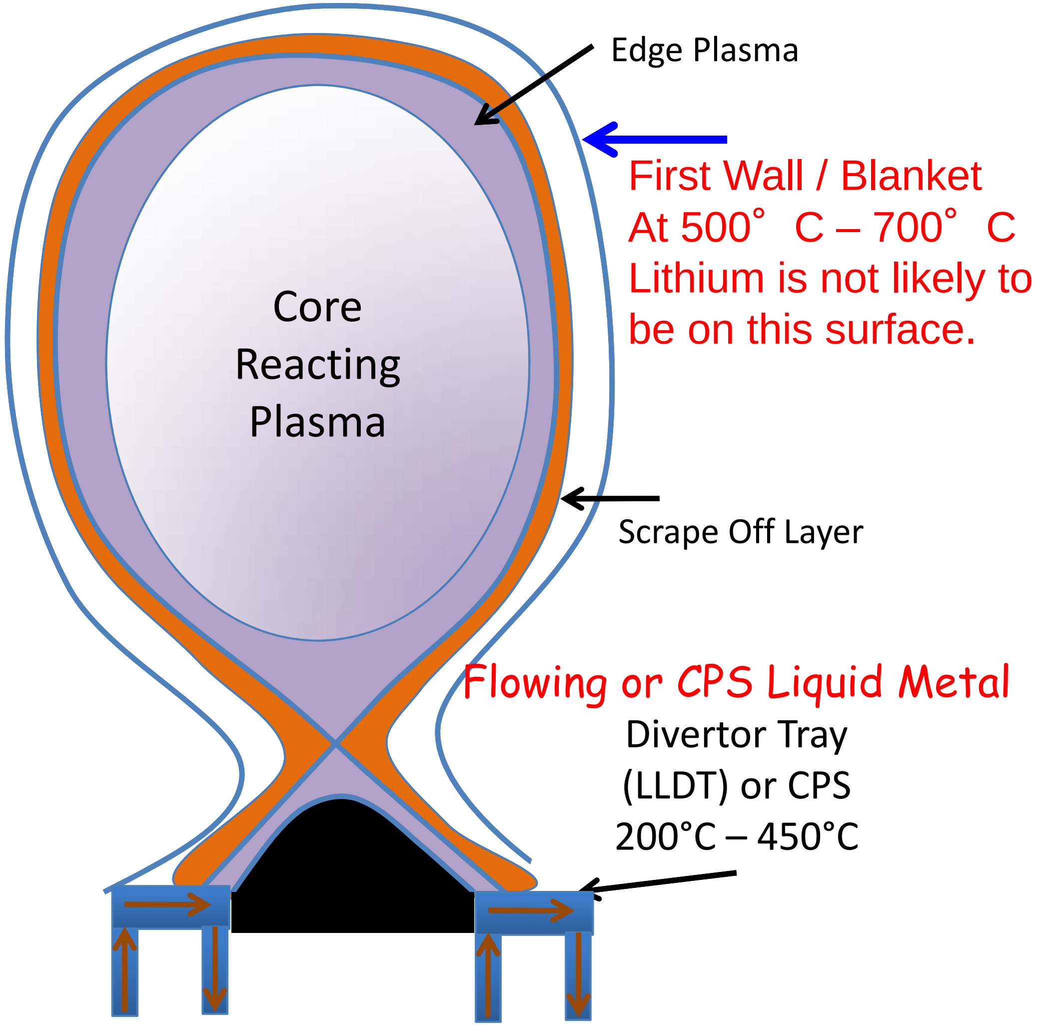
# T retention

- Not an issue for Ga, Sn or Sn/Li (ret< 0.1%)
- FW in a Reactor T>600ºC
- Not likely an issue in a Reactor based on LMs
- H recovered from CPS without full Li evaporation
- Warning: NO experience on high T FW operation available to date. W chosen for ITER due to T retention issues!

- Can be used for particle pumping at T<400ºC in flowing Li schemes!...but He pumping? Not clear…
- *Low recycling → Enhanced confinement (Li) ?*
- *High Recycling → Strong Pumping, low Te div ?*

Open options:Conflicting interests!

# Integration Issues




**Issues:**

- **Tritium Retention**
- He exhaust
- **Power exhaust**
- Plama Contamination
- Plasma Confinement
- Material lifetime
- Neutron activation
- **FW+Div Target compatibiliy**

# Choosing the right CPS structure

- Basic limitation of porous structures: poor thermal conductivity:

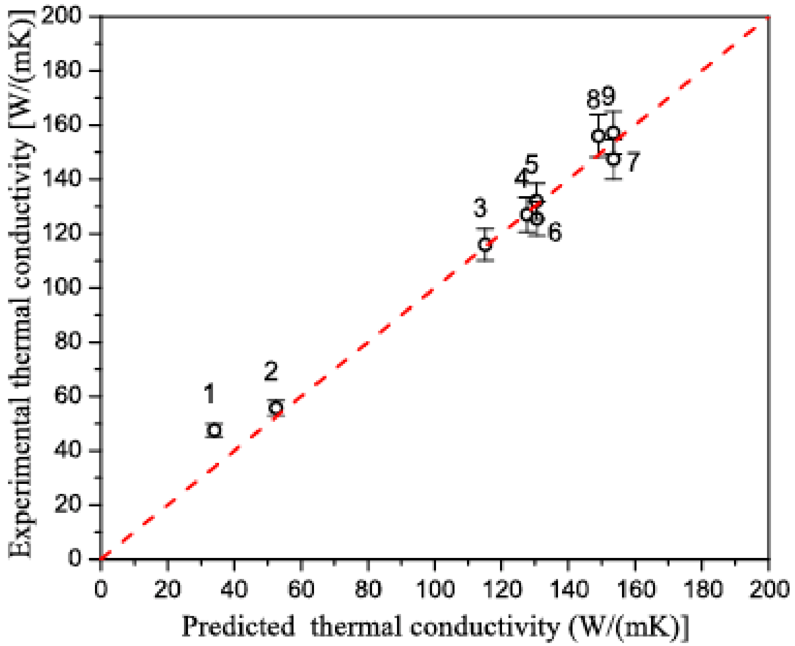



FIG. 3. Correlation of experimental and predicted thermal conductivity of sintered tungsten samples. The dashed line indicates the equality of predicted and experimental values.

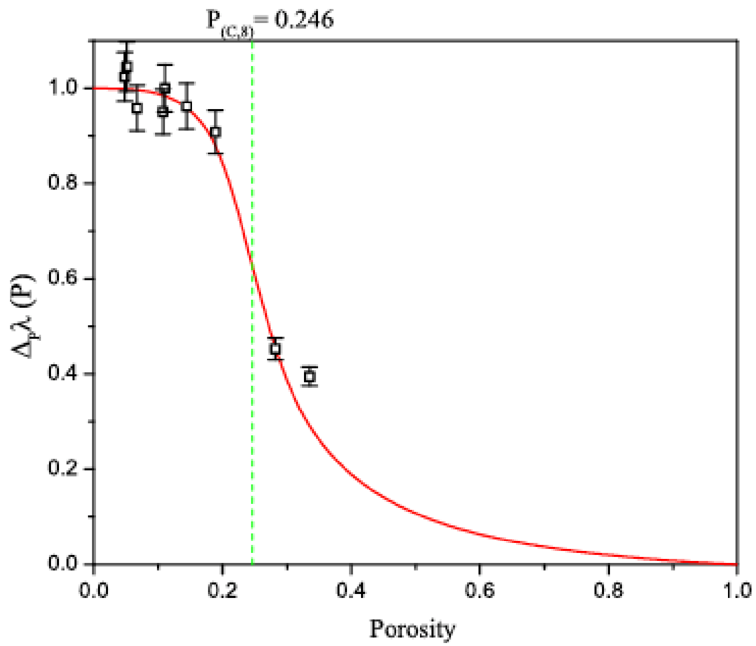



FIG. 4. Thermal conductivity degradation of sintered tungsten induced by the porosity only. The critical porosity is indicated by the vertical dotted line.

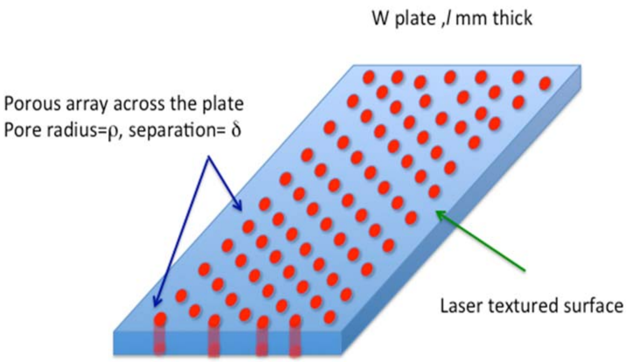
**Experimental study of the thermal conductivity of sintered tungsten: Evidence of a critical behaviour with porosity**

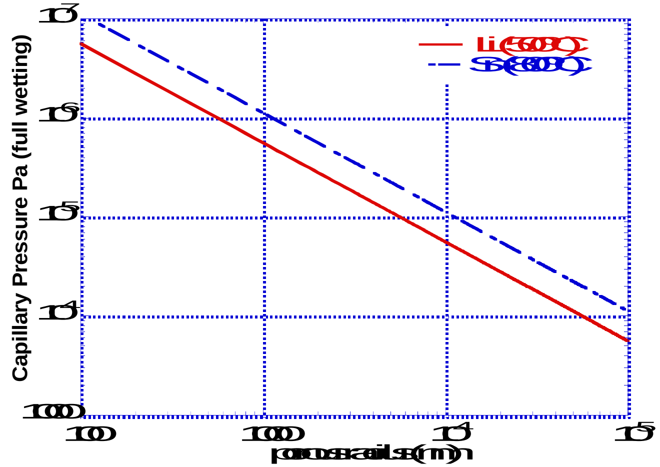
Aïmen E. Gheribi, Jean-Laurent Gardarein, Emmanuel Autissier, Fabrice Rigollet, Marianne Richou, and Patrice Chartrand

Applied Physics Letters **107**, 094102 (2015);

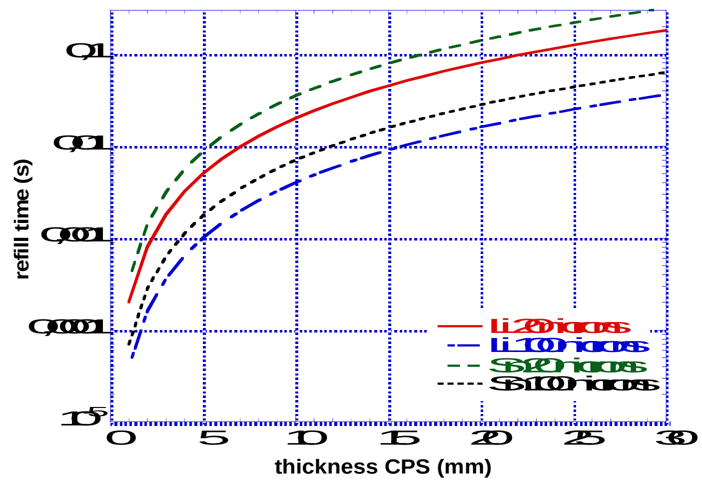
# Choosing the right CPS structure

- Basic considerations:Capillary pressure/refilling time/Heat tansmission+ thickness of top LM layer



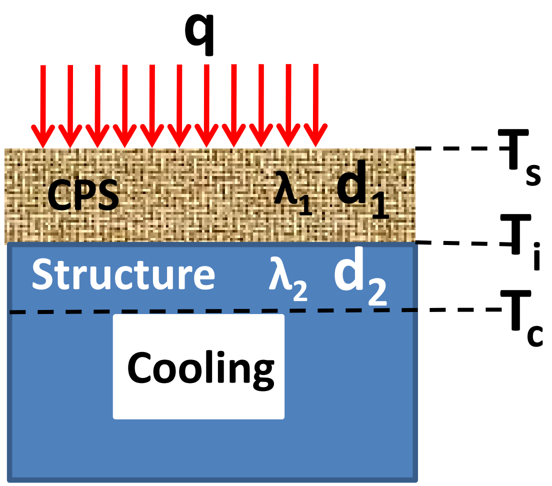



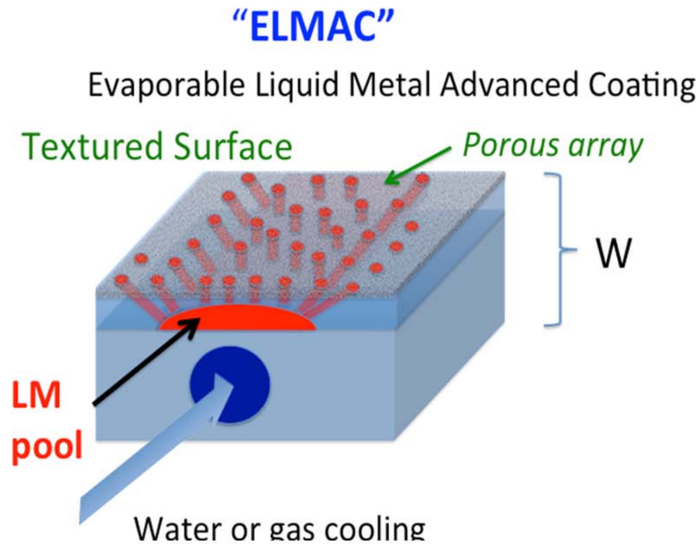

$P=2\sigma \cos\theta/r$



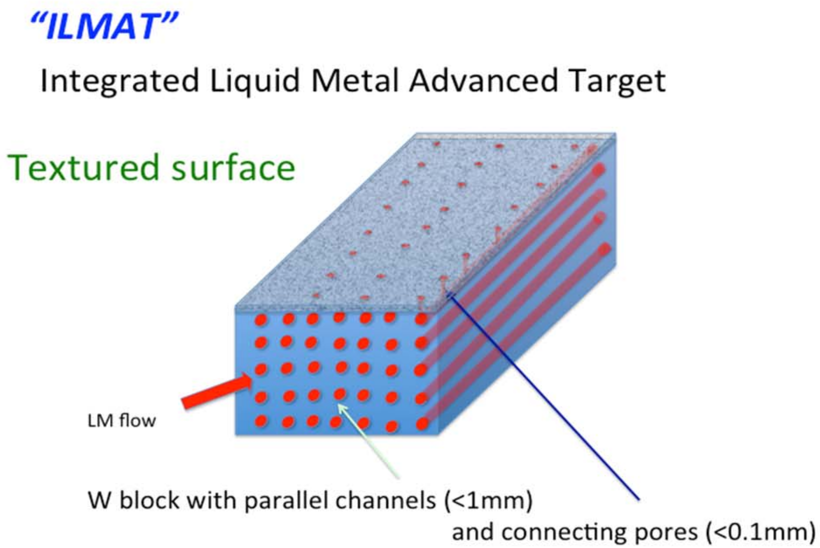

$t = 4l^2 \eta / r.\sigma$

# Optimizing the heat transfer from the LM




| | Ts (°C) ($T_w$=150 ) 1% FLUX | $d_1$(mm) (CPS) | $d_2$ (mm) (struc) | P ($MW/m^2$) |
|---|---|---|---|---|
| Sn optim. | 1277 | 1 | 3 | 28.75 |
| Li optim. | 480 | 1 | 3 | 8.25 |

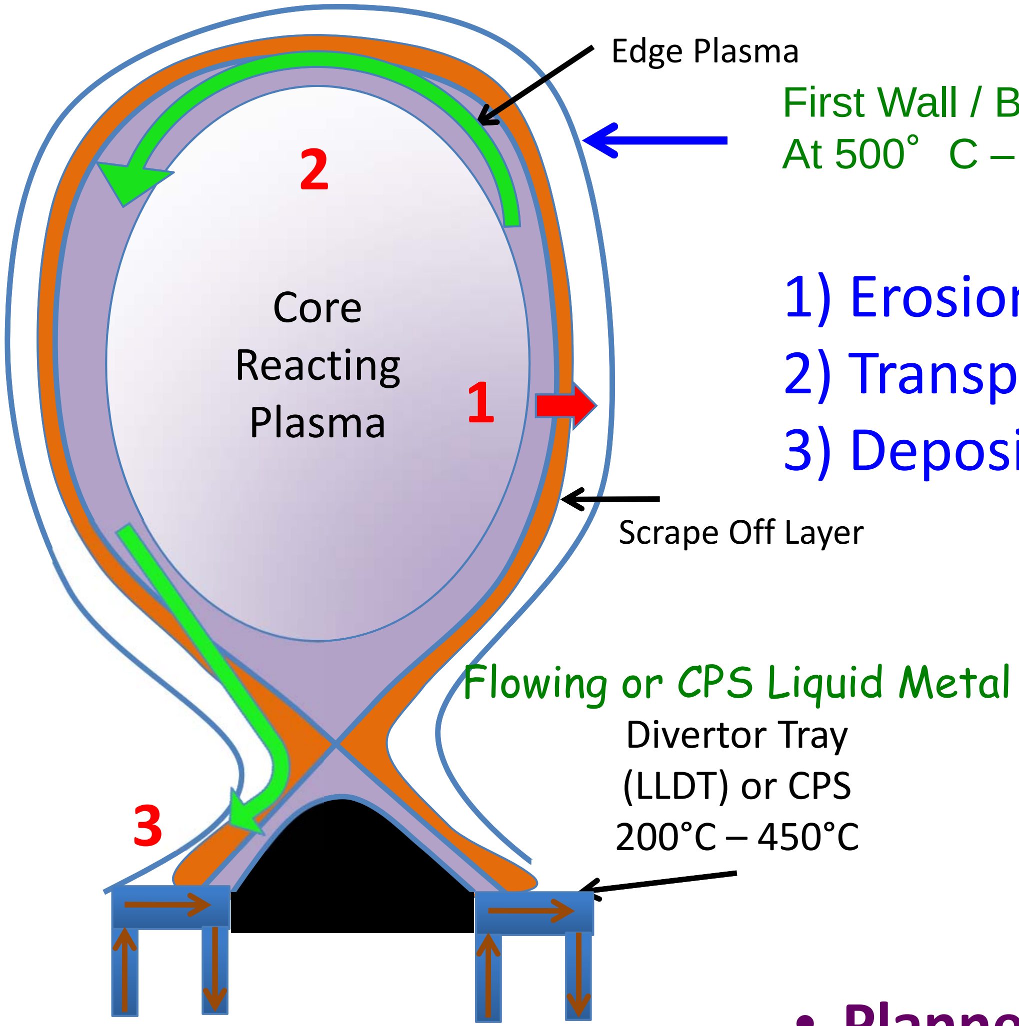



→ **But > 99% redep?**

→ **Interfacial Resistance?**

# FW+Divertor interactions

- Let's assume a simple FW made of W or low activation steel and a LM target divertor.




1) Erosion of FW by LM ions
2) Transport from FW to inner divertor
3) Deposition on inner divertor CPS

E.g. Li implanted on W
- Mechanical properties ?
- T retention?
- Etc…
- **W→ Li/Sn?**

- **Planned Experiments (PISCES-B)**

# Conclusions

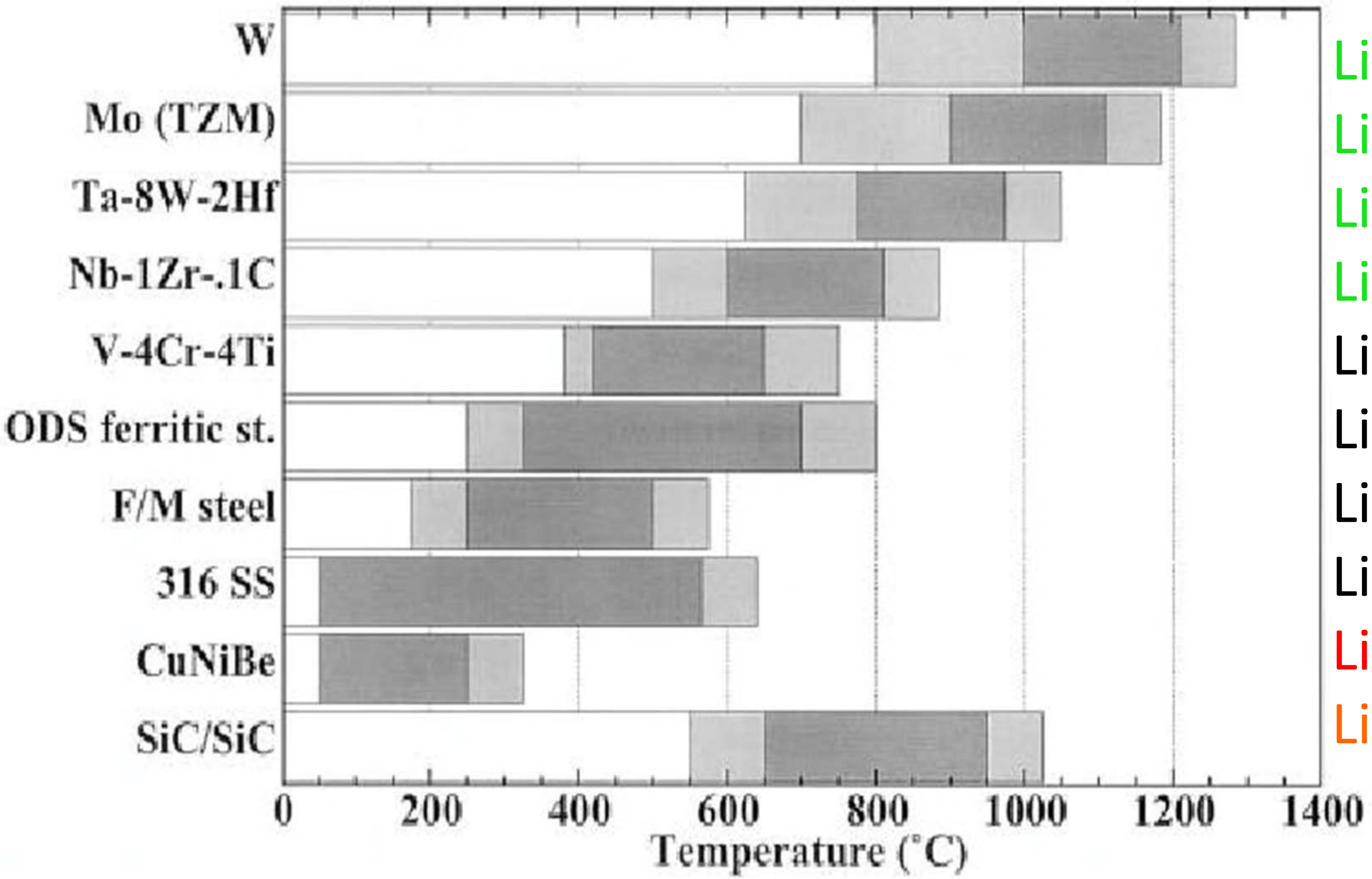
- Liquid Metals: a solid alternative for PFM in a Reactor
- Conservative approach: use them as advanced coatings of standard PFC materials:Benefits from present research on solid targets (ELMAC concepts)

- A significant degree of maturity achieved for some concepts
- A true International Undertaking
- Choosing the best (feasible/realistic) option:

More experiments/ modelling mandatory

**Thank you…**

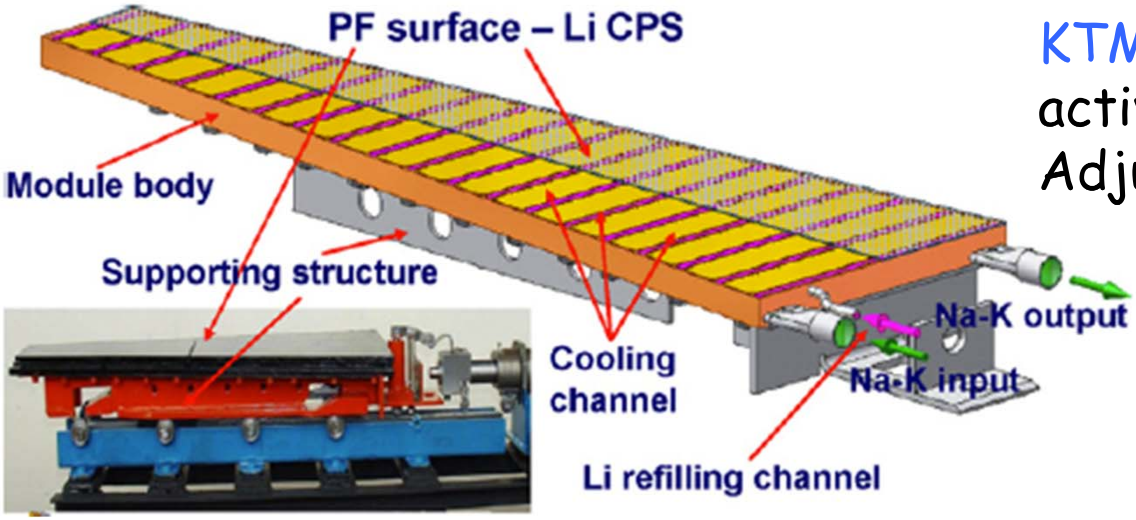
# Liquid metal-structural compatibility



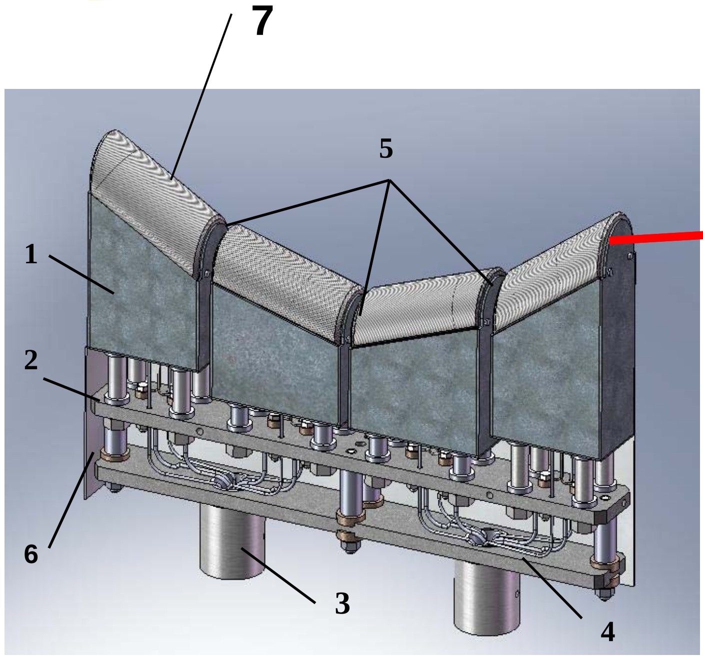

Li, Sn, Ga
Li, Sn, Ga
Li, Sn, Ga?
Li, Sn, Ga?
Li, Sn?, Ga?
Li, Sn, Ga
Li, Sn, Ga
Li, Sn, Ga
Li, Sn, Ga
Li?, Sn, Ga

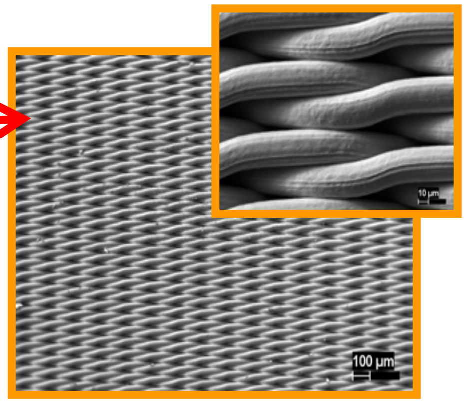
Zinkle and Ghoniem, **FED** 2000. (Sn and Sn-Li used interchangeably) “The Liquid Metal Handbook” Liquid-metals handbook”, United States Office of Naval Research. U.S. Govt. Print. Off. 1950. (Gallium estimates)

# Li CPS Systems




KTM :
actively cooled by NaK
Adjustable divertor Targets




TJ-II:
Inertially cooled
Movable
Heatable
Diagnosed

# Examples

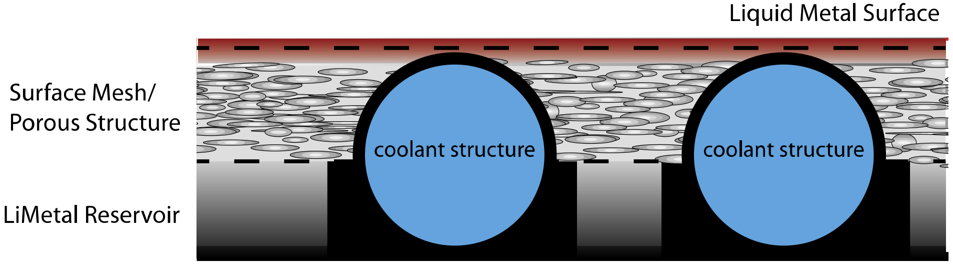
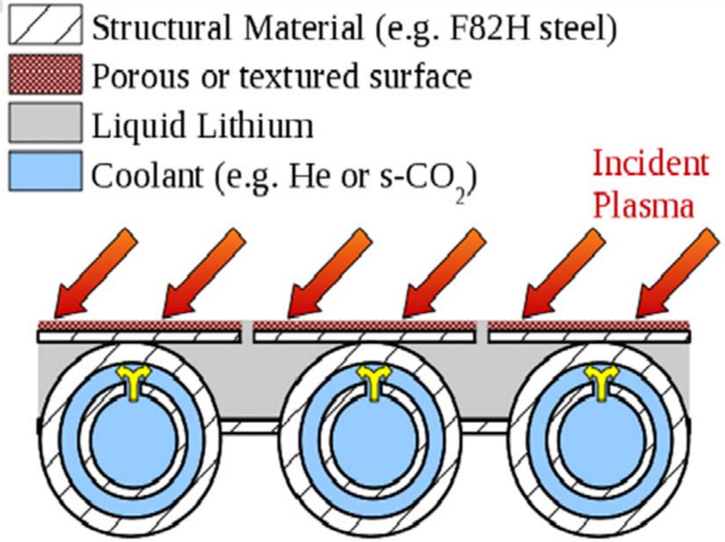
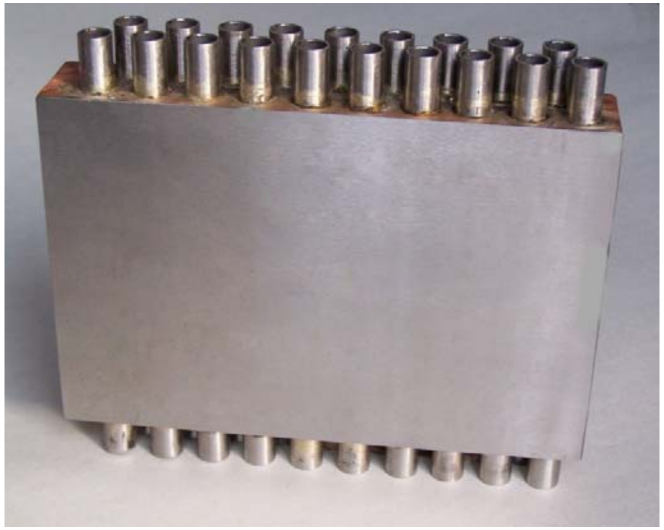



**Figure 2.** CPS components.

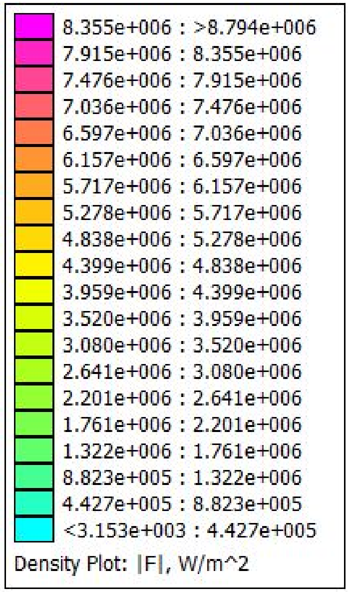
Julich

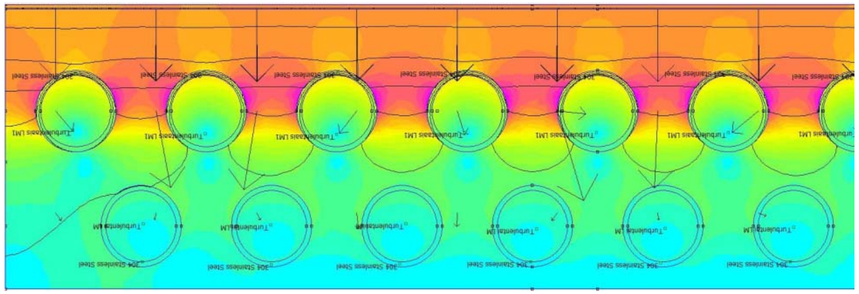



NSTX



Latvia



Tube thickness: 0.5 mm

# International Activities on LMs

Several comprehensive reviews available:

**- APEX Reports:**

M.A. Abdou et al. Fusion Eng. Des. 54 (2001)181 and related papers

- **ISLA Reports:**

  Y. Hirooka et al Nucl. Fusion 50 (2010) 077001

  M. Ono et al Nucl. Fusion 52 (2012) 037001

  G. Mazzitelli et al Nucl Fusion 55 (2015) 027001

**Also:**

- Y. Hirooka et al. TOFE-2014 Proceedings. Fusion Science & Technology, in press.
- J W Coenen et al. Phys Scr. T159 (2014) 014037
- M A Jaworski Plasma Phys. Control. Fusion 55 (2013) 124040

# International Activities on LM

- **USA:**

- Princeton: NSTX (U), LTX: Li on high Z porous systems. Impact on ELM pacing, H mode, pressure profiles, global confinement, …*Ambitious Scientific Program on LMs 2015-2020.*
- Urbana Uni: LiMIT, Vega Stellerator, TELS (ELM+LiMIT,..)

- **China:**

- East+ LH-7 LM research: Coatings, free flow, LiMIT and CPS tests. Performance of W+Li combinations.

- **Japan:**

- VEHICLE facility: Test of moving-element conceptual divertors
- Electrostatic stirring of Liq. Lithium pools
- ….

Updated summary to be presented in the next ISLA Conference in Granada, 28-30 Sept 2015

# International Activities on LM

- Europe:

*Within the EuroFusion Road Map. Tasks PFC and DTT.*

- FTU: Actively cooled Li and Sn CPS limiters
- TJ-II: Liquid Lithium Limiters and Li coatings. Effect of high SEE, capillary effects. H retention.Tests of Li/Sn
- Magnum PSI and PILOT: H retention, vapor shielding on Li and Tin
- ISTTOK: Tests of Ga, Sn and Li/Sn. H retention/vapor shielding/erosion
- Greece: Modelling activities on capillary effects
- ENEA/CNR Milano: Plasma exposure of Sn and Li/Sn (GYM)
- Latvia: LM wetting/corrosion activities
- Slovakia: LIBS studies on Li/Sn and W/Li
- ….

- Russia:

- T-10 and T11-M LM operation
- Long standing LM research
- Pioneers on CPS concepts (Red Star)
- Emitter-Receiver proposal
- Support on KTM LM divertor
- …