Agenzia nazionale per le nuove tecnologie,
l'energia e lo sviluppo economico sostenibile

Proposal for a high Z liquid metal divertor

Nov 8, 2022 IAEA Headquarters - 4th TMDC

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Proposal for a high Z liquid metal divertor

IAEA Headquarters - 4th TMDC

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Introduction

Introduction: power exhaust challenge

One of the main challenges in the European fusion roadmap is to design a power exhaust system able to withstand the large loads expected in the divertor of a future fusion power plant.

Actual strategy:

- development of plasma facing components
- selection of the divertor geometry and of the magnetic flux expansion
- removal of plasma energy before it reaches the target via impurity radiation
- recycling and increase of density, lowering the temperature close to the target → detached regime

"A reliable solution to the problem of **heat exhaust** *and helium removal is one of the main challenges in realising magnetic confinement fusion."*

European Research Roadmap to the Realisation of Fusion Energy - 2018

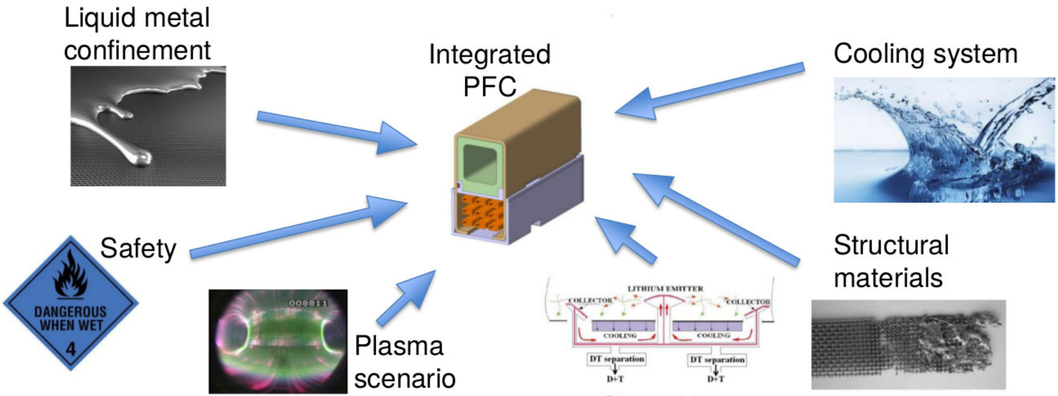
Introduction - Motivations

Why study liquid metals in a tokamak environment?

- Liquid Metals (LM) are self-healing/renewable plasma-facing material
- LMs are less sensitive/immune to the neutron damage
- LM can be considered a long lifetime plasma-facing component
- Vapour shielding effect against (e.g. fast transient) increasing heat load

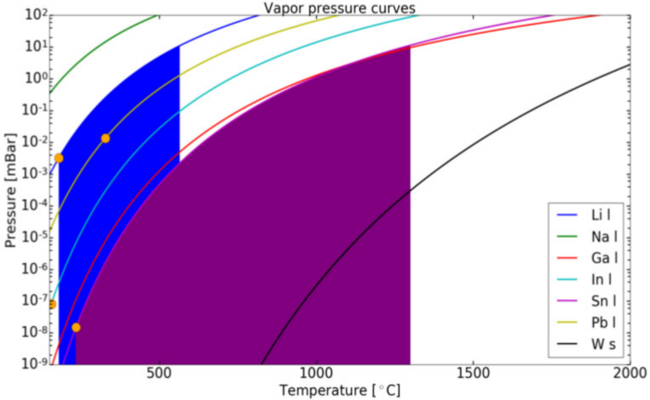
Introduction: Liquid metals in Tokamaks

Many subsystems need to be combined into an integrated component

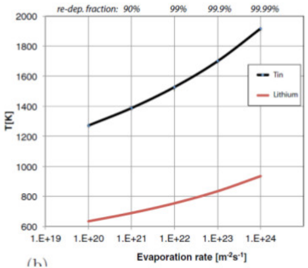


Introduction: Operative window

Most relevant LMs and their vapour pressure



- The evaporative flux is one of the main issue for the steady state operation



[J.W. Coenen *et al.* Phys. Scr. **T159** (2014) 014037]

Liquid metals experiments: lesson learned

LM experiments: possible approaches

LMs in a fusion reactor, flowing or not flowing?

Flowing

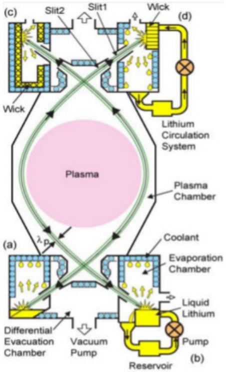
Static

Static LM approach

Take it static

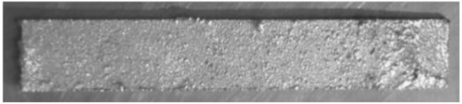
Vapor box

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



CPS-based
Capillary Porous System

- Particle and power exhaust
- Plasma Contamination
- Material lifetime
- Neutron activation
- Target compatibility



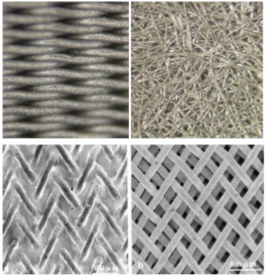
Static LM - Capillary Pore System - CPS

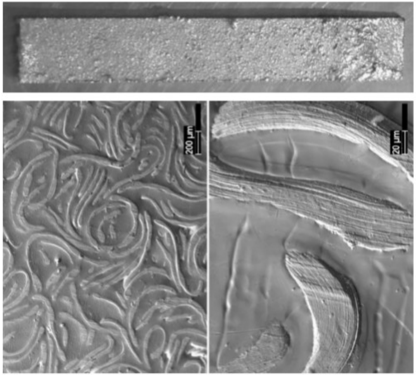
Capillary pressure can prevent splashing and droplet formation

CPS capillary pressure *Pc* is determined as:

$$P_c = \frac{2 \cdot \sigma \cdot \cos\theta}{r_{eff}}$$

- θ – wetting angle
- r_{eff} – CPS pore radius
- σ – surface tension

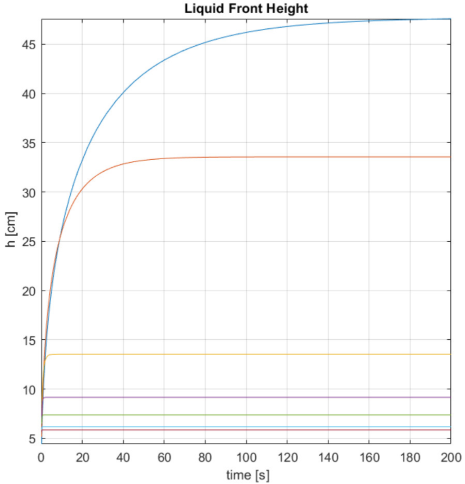




CPS: simulations vs experiments

Wetting test

Modified Lucas-Washburn (MLW) equation plotted for **liquid tin**: curves are plotted using different values of the pore radius ($300\mu m$ to $30\mu m$) Maximum equilibrium height increases for decreasing pore radius.



Recent experiment

Several experiment in EU are investigating and testing CPS technology

- Exposure of different CPS in Magnum-PSI [1]
- Test in the OLMAT (Optimization of Advanced Liquid Metal Targets) facility [2]
- Experiements in COMPASS with a small CPS in the divertor region [3]
- Exposure of CPS on GLADIS and ASDEX-U (using divertor manipulator)

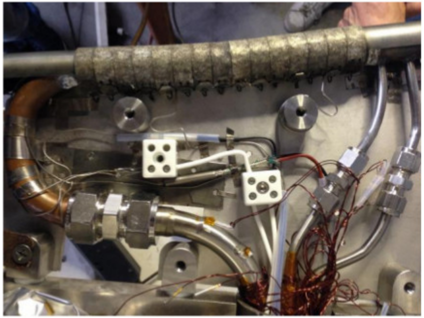
[1] Reducing tin droplet ejection from capillary porous structures under hydrogen plasma exposure in Magnum-PSI, J.G.A. Scholte et al.

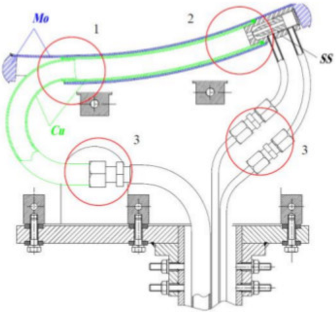
[2] Design and Testing of Advanced Liquid Metal Targets for DEMO Divertor: The OLMAT Project, D. Alegre et al.

[3] Overview of power exhaust experiments in the COMPASS divertor with liquid metals, R.Dejarnac et al.

Liquid Tin Limiter experiments

Liquid tin limiter tested for the first time in a tokamak environment



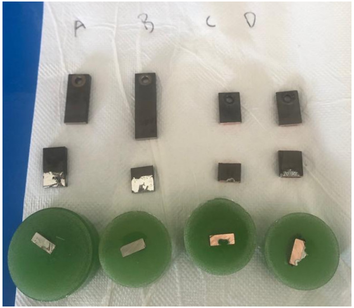


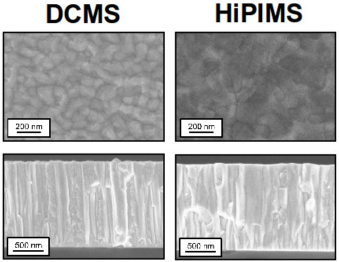
- Flexible and easy layout
- Operative temperature windows have been extensively studied
- Survived with no damage at all hundreds shots, tens disruptions

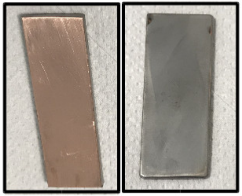
Prevent tin corrosion

- Tin corrosive attack is very aggressive
- W is compatible up to high temperature
- Structural elements have to be protected
- Several deposition strategies are under investigation

PoliMI team contribution







Liquid Metal Divertor (LMD) design proposal

Cooling the static LM PFC

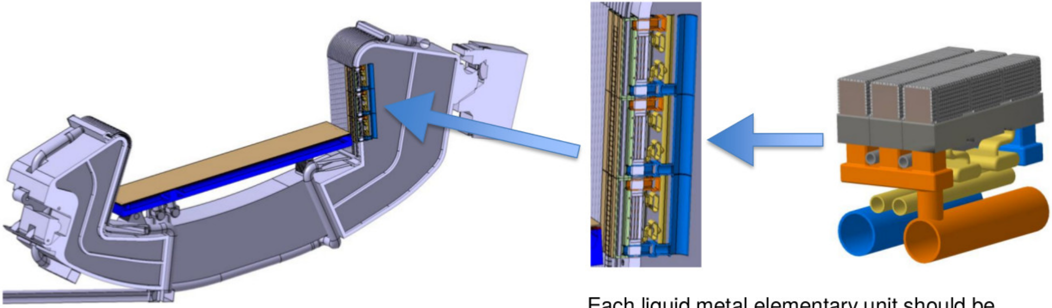
Thermal resistance, R_t , is a key parameter. At the steady state we can consider:

$$Q = \frac{T_{surf} - T_{coolant}}{R_t}$$

- LM allow to reduce the thickness O(mm) $\rightarrow$ lower R_t
- Different cooling system are under study

Low surface temperature is important to avoid evaporation

Proposal for a Liquid Metal Divertor

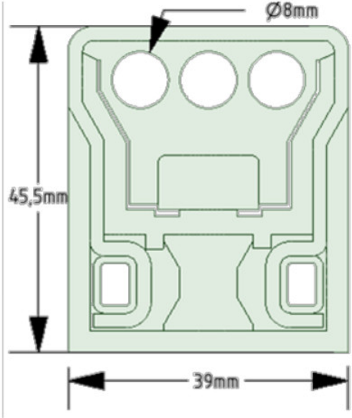


- The *elementary liquid metal units* can fit the standard DEMO cassette scheme.

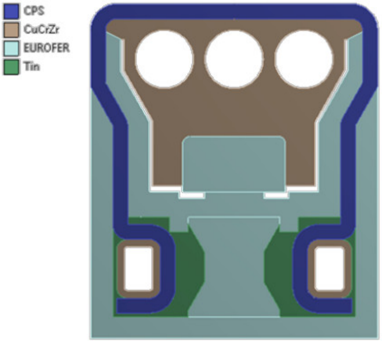
Each liquid metal elementary unit should be provided by:

- Coolant
- LM reservoir and refill line
- Heating system
- Anti-corrosion layer

LMD proposal: cross section

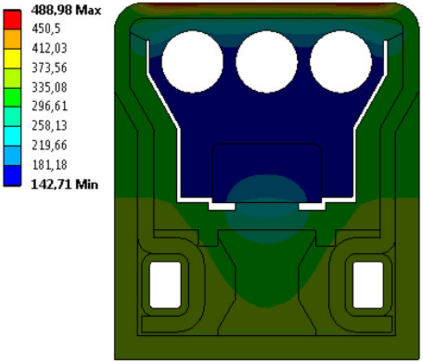
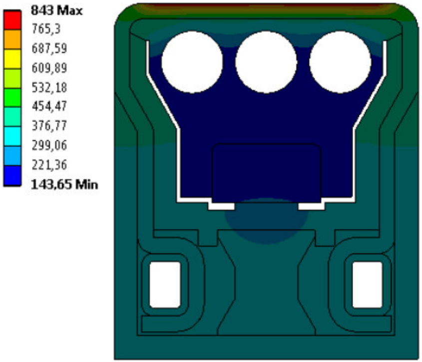


Gas temperature
T = 350°C



Water hydraulic parameters
T_{bulk} = 140°C
p= 5 MPa
v= 12m/s

LMD proposal: thermal analysis

Heat flux = 10 MW/m²	Heat flux = 20 MW/m²
	

Tin evaporation is negligible because the CPS surface temperature is sufficiently low

LMD proposal: W70-Cu30 advanced material

W Monoblock

$T_{bulk} = 120°C$
$v = 12 m/s$
$p = 40 bar$
$D_{int} = 12 mm$
$\downarrow$
$CHF\ 45.3\ MW/m^2$
$\downarrow$
CHF $\perp$ PFC
$f_p = 1.7$
$26.8\ MW/m^2$
CHF margin 1.33

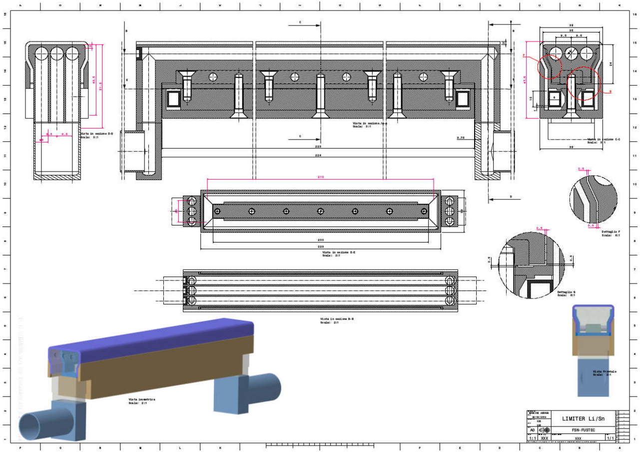
LMD (CuCrZr)

$T_{bulk} = 140°C$
$v = 12 m/s$
$p = 50 bar$
$D_{int} = 8 mm$
$\downarrow$
$CHF\ 40\ MW/m^2$
$\downarrow$
CHF $\perp$ PFC
$f_p = 1.38$
$28.5\ MW/m^2$
CHF margin 1.42

LMD (W-Cu)

$T_{bulk} = 120°C$
$v = 12 m/s$
$p = 50 bar$
$D_{int} = 8 mm$
$\downarrow$
$CHF\ 46\ MW/m^2$
$\downarrow$
CHF $\perp$ PFC
$f_p = 1.42$
$32.6\ MW/m^2$
CHF margin 1.6

Small scale mock-up



Starting from the FTU Liquid Metal Limiters experience:

- static CPS approach
- enhanced cooling capability
- easy and flexible design
- thermal analysis and EM calculation have been performed

Mock-up - work in progress

Two small scale mock-ups have been manufactured (CuCrZr and W70-Cu30).

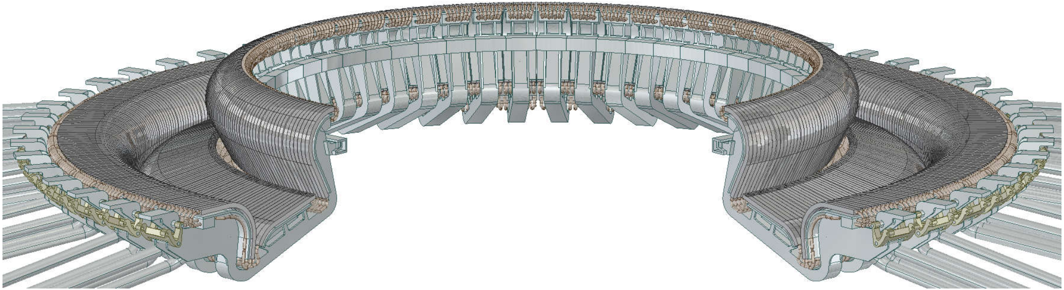
A few steps are still missing:

- choice for the W coating technique - reliability on complex geometry is mandatory
- assembly - including wetting

The Divertor Tokamak Test facility

DTT - divertor overview

The DTT Divertor: flexibility to test several magnetic configurations and alternative PFC such as liquid metals



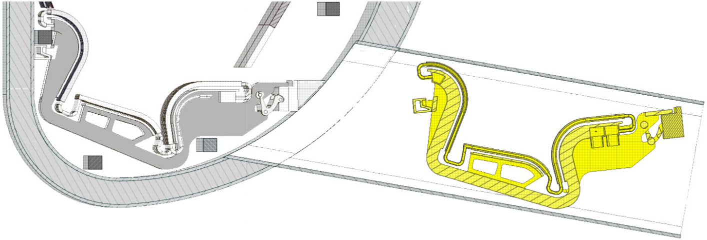
See *An overview of the conceptual design of the plasma-facing components of the DTT divertor*
Giacomo Dose - Poster session II

DTT - divertor technological tests

Four location devoted to technologies further investigation

Easily accessible and removable: extraction of the central cassette without removing pipes of the two adjacent.

Preferential location eventually supplied by a dedicated cooling system has been allocated.



Conclusion

Conclusion

- LM seems a viable alternative PFC solution
- Recent experiment are investigating LMs PFC in the risk mitigation framework
- The LM community is growing

The 7th INTERNATIONAL SYMPOSIUM ON LIQUID METALS APPLICATIONS FOR FUSION (ISLA-7)
Chubu University, Kasugai, Aichi, JAPAN
Dec. 12th -Dec. 16th, 2022

Future work

- Finalizing the mock up assembly
- Test in linear device the technological aspects
- Test in an integrated plasma scenario

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