EUROfusion

Development of a liquid metal divertor solution for DEMO

T.W. Morgan
(on behalf of the PRD-LMD team)

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PRD-LMD team

1. J.G.A. Scholte, F. Romano the Magnum team
2. S.S. Herashchenko, V.A. Makhlai, I.E. Garkusha, Yu.V. Petrov, N.N. Aksenov, O.V. Byrka, V.V. Cheboratev, N.V. Kulik, V.V. Staltsov, P.B. Shevchuk
3. R. Dejarnac, J. Horacek, F. Jaulmes, J. Cecrdle
4. I. Kaldre, L. Buligins, I. Grants, O. Mikanovskis, K. Kravalis
5. I.Ivanova-Stanik, V. Pericoli Ridolfini
6. D. Horsley, F. Chaudry, T. Barrett, S. Desai, J. Freemantle, E. Organ
7. G. F. Nallo, E. Bray, C. Marchetto, F. Subba, T. Luda di Cortemiglia, C. Angioni, D. Fajardo, E. Fable, R. Zanino
8. E. Oyarzabal, F. Tabares, D. Alegre, A. de Castro, M. Liniers, D. Tafalla, E. de la Cal, I. Voldimer and the OLMAT team
9. L. Bana, D. Vavassori, V. Russo, M. Bugatti, D. Dellasega, M. Passoni
10. M. Iafrati, S. Roccella, G. Mazzitelli
11. K. Krieger, R. Dux, A. Manhard, M. Balden, V. Rohde, D. Brida, S. Elgeti, M. Faitsch, A. Herrmann, K. Hunger, P. de Marne

1 DIFFER Dutch Institute for Fundamental Energy Research

2 KIPT

3 IPP

4 UNIVERSITY OF LATVIA ANNO 1919

5 IFPiLM

6 CCFE CULHAM CENTRE FOR FUSION ENERGY

7 Politecnico di Torino

8 Laboratorio Nacional de Fusión Ciemat

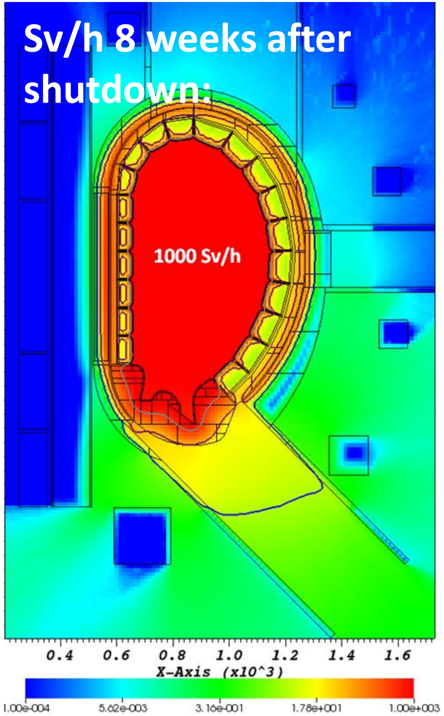
9 POLITECNICO MILANO 1863

10 ENEA

11 IPP Max-Planck-Institut für Plasmaphysik

Why LMDs for DEMO?

Challenge for PFCs:
avoiding component failure in DEMO



Courtesy Ch. Bachmann

Importance of reliability for heat exhaust solution for fusion economic viability

Need to avoid reaching component failure

- Loss of coolant accident (LOCA)
- Excessive erosion into core
- Too damaged to risk continued use

Any large unmitigated ELM or disruption could lead to failure (melting, LOCA)

Planned replacement will require >6 months

PFC failure has high risk and impact

Challenges for DEMO divertor design

Solid PFC

- **Strong limit** on P_{sep} (dictates design)

    delicate radiation balance

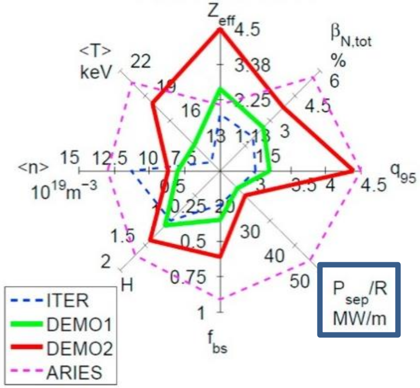
- Need extremely good (active) **control**:

    <1 unmitigated disruption?

    ELM free operation(?)

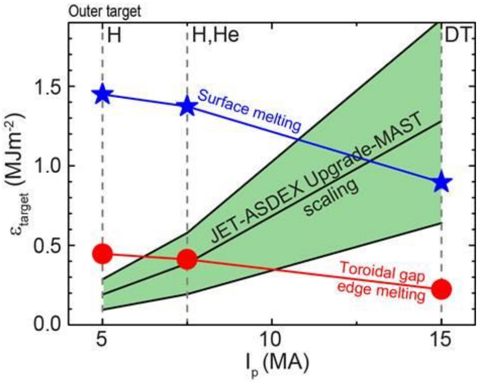
- **Erosion** gives one of upper lifetime limits divertor and **neutrons** degrade properties over time

    requires replacement/2fpy



Design space for DEMO

G. Federici FED (2016)



ELM damage for ITER

Potential advantages liquid metals

Liquid PFC

- **Higher P_{sep} possible** due to large power removal in SOL
  [Goldston Phys. Scr 2016]

  More robust scenario?

- Negative feedback from evaporation; **vapour shielding protection** of substrate + replenishment
  [Rindt Nucl. Fusion (2018)]

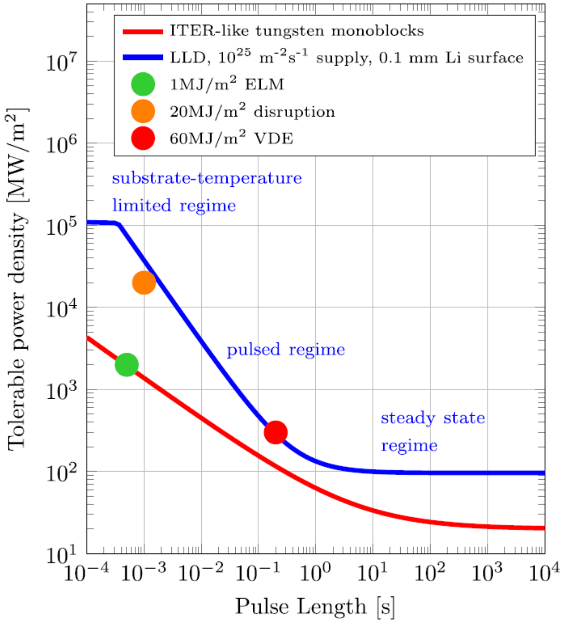
  ELMs allowed?

  De-risk operation as disruptions survivable?

- **Replenishment** removes erosion concern and neutrons **limited effect** on LM and W substrate performance
  [Rindt Fusion Eng. Des. (2021); Rindt Nucl. Fusion 2019]

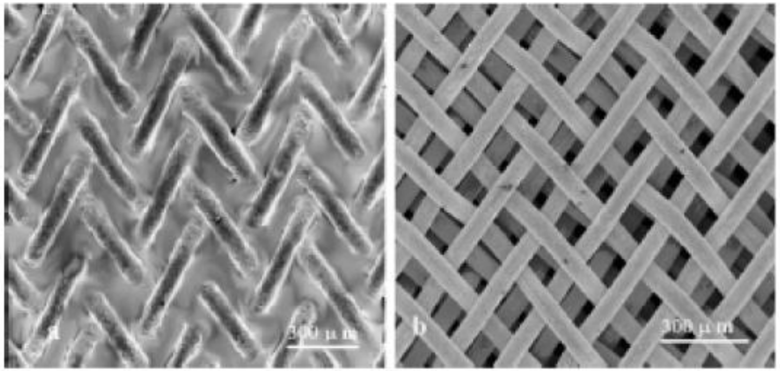
  Longer divertor lifetime?

Power density limits in principle higher for LMs



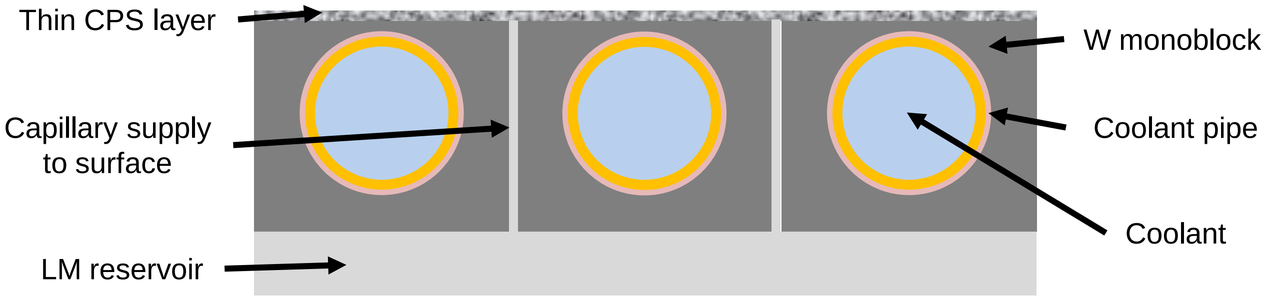
Rindt NF (2018)

Capillary porous structures (CPSs) create conduction based stabilized PFCs



Evtikhin JNM (1999)

- Replace solid surface with liquid
- MHD forces (**j**x**B**) destabilize liquids in tokamaks (droplets)
- Use surface tension/capillary refilling
- Replace top region with this combined material



Design criteria overview: performance

Design requirement	Sn	Li
Must tolerate 10 MW m^{-2} in nominal operation	✓	✗ (✓)
17-21 MW m^{-2} during slow transients 3-10 s	✓	✗ (✓)
Heat load < 5 MW m^{-2} outside strike points	✓	✓
Withstand ≥1 disruption (80 GW m^{-2} 4 ms)	✓	✓
Coolant 40% safety factor CHF	✓	✓
Tritium inventory in-vessel <730g	✓	✗
Evaporation must not significantly reduce fusion output during normal operation	✓ 1250 °C	✗ (✓) 690 °C

Cannot simultaneously satisfy high heat loads and low evaporation rate for Li

Tritium inventory control with Li requires continual active removal

Design criteria overview: compatibility

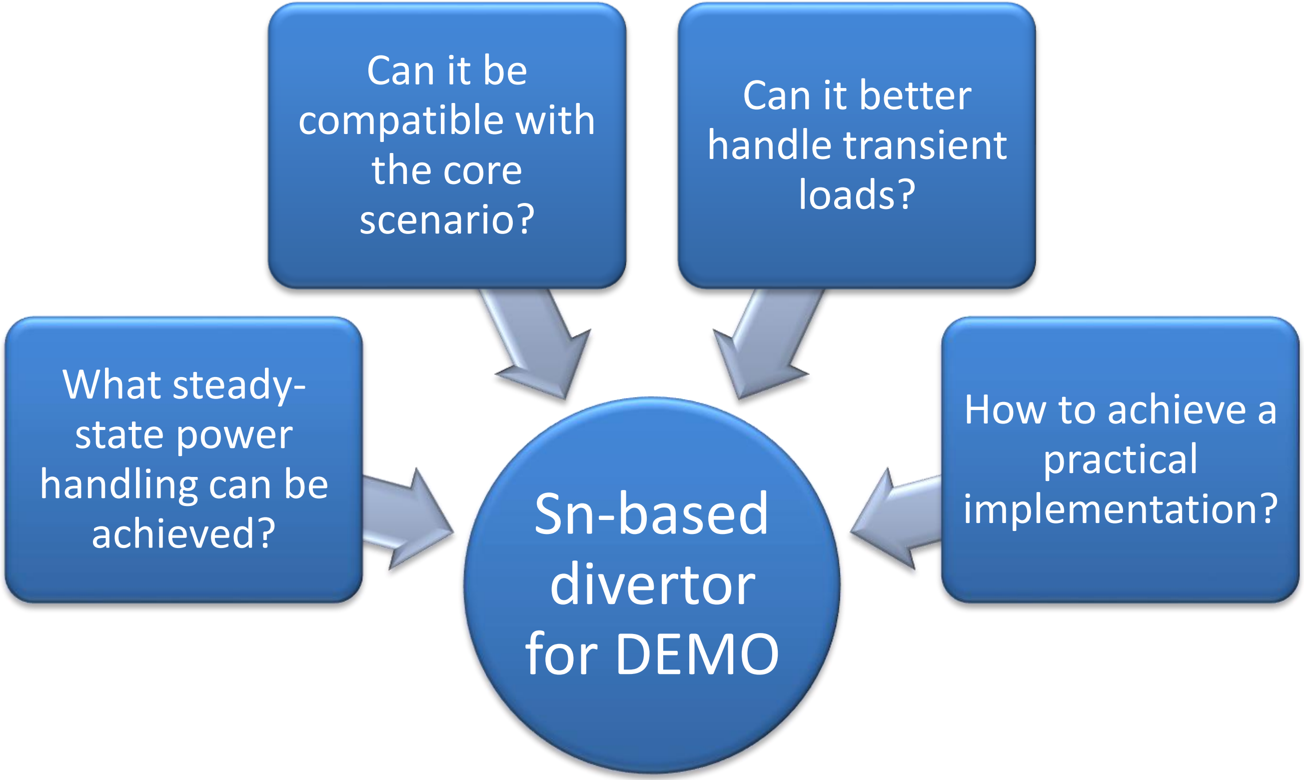
Design requirement	Sn	Li
High recycling divertor	✓	✘
Activation must be kept to limits for intermediate level waste	✓	✓
Lifetime 2 fpy	✓	✓
70 cm high vertical target	✓	✓
Need to be able to re-wet in-situ	✓	✓
Withstand atmosphere for 2 months during maintenance	✓	✘
Withstand 200 °C bake during startup	✓	✓
No major design changes to in-vessel components, diagnostics, 1^{st} wall	✓	✘

Li would act as low recycling surface and result in significant changes to the operational mode of DEMO

Li better suited for e.g. vapour box concept and is not further considered here

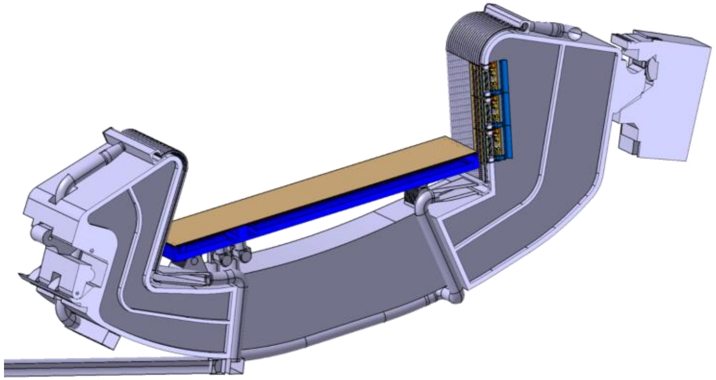
Sn chosen as candidate LM for this application

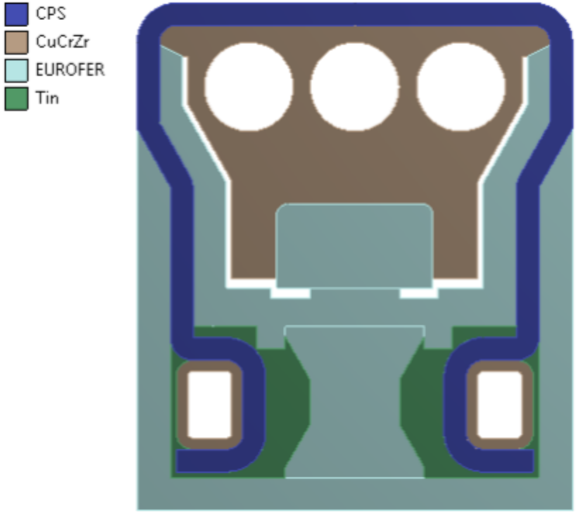
Development questions

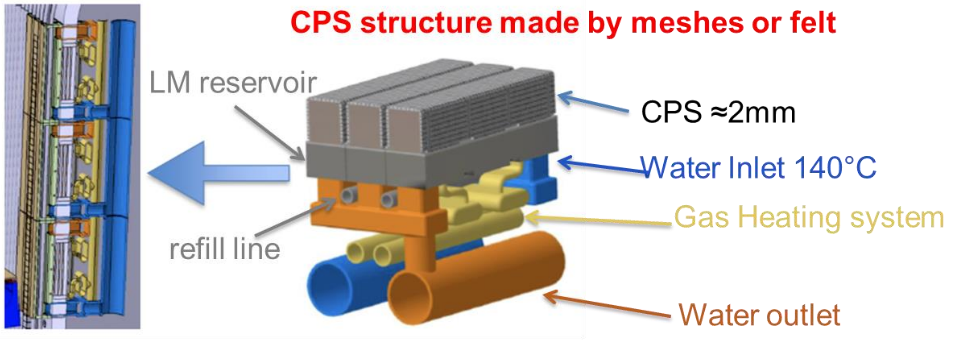


What steady-state power handling can be achieved?

Conceptual design (ENEA)







Water hydraulic parameters

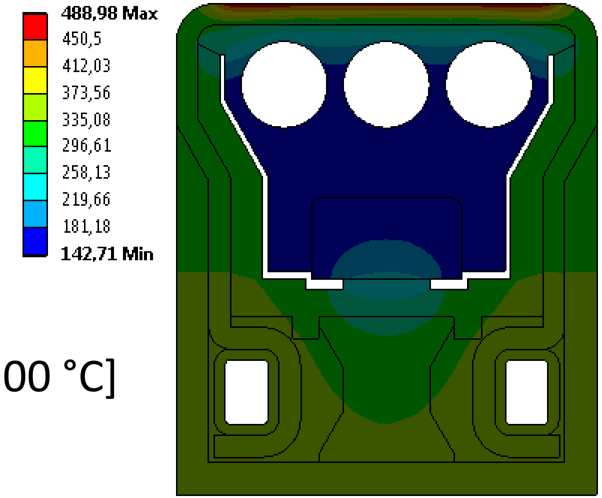
T_{bulk} = 140°C
p= 5 MPa
v= 12m/s

Roccella Journal of Fusion Energy (2020)

PFU thermal analysis (ENEA)

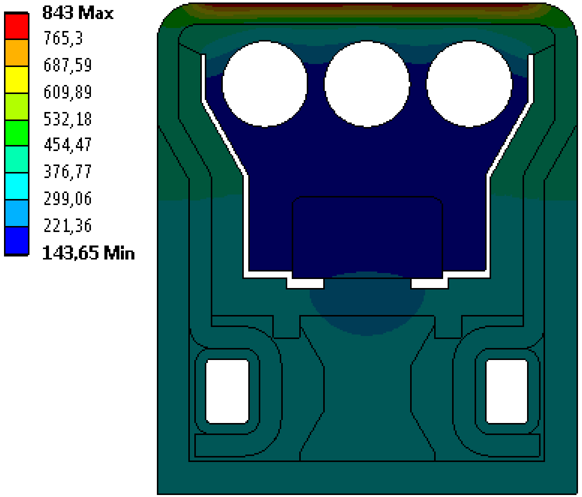
Heat flux = 10 MW/m^2

<500 °C



[T$_{Wmono}$~1200 °C]

Heat flux = 20 MW/m^2



<850 °C

[T$_{Wmono}$~2400 °C]

In both cases evaporation is negligible because CPS surface temperature is below 1000 °C

Roccella Journal of Fusion Energy (2020)

Can it be compatible with the core scenario?

SOLPS-ITER modelling with self-consistent PWI for Sn (PoLiTo)

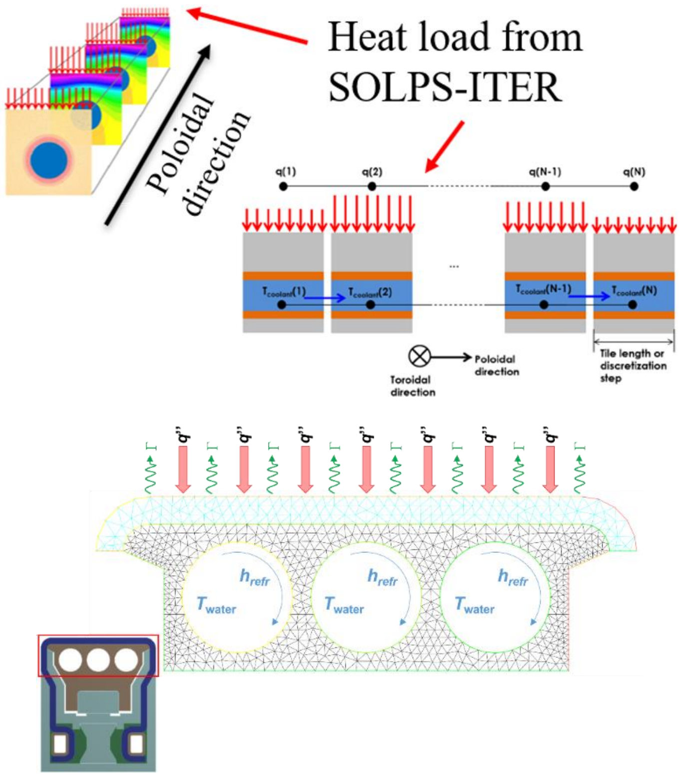
SOLPS-ITER modelling with additional Sn processes from ADAS database

2D FE model for heat conduction in each section

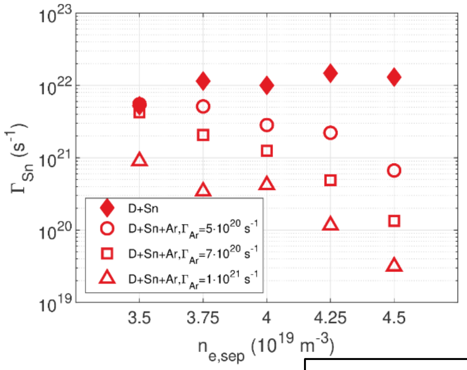
- Specified heat transfer coefficient and coolant temperature
- Imposed heat flux from SOLPS-ITER on PFS
- Consider evaporation, thermal sputtering
- Temperature-dependent properties

Simplified treatment of LM-filled CPS layer on top of substrate:

- Solid layer with averaged thermal properties evaluated by law of mixtures

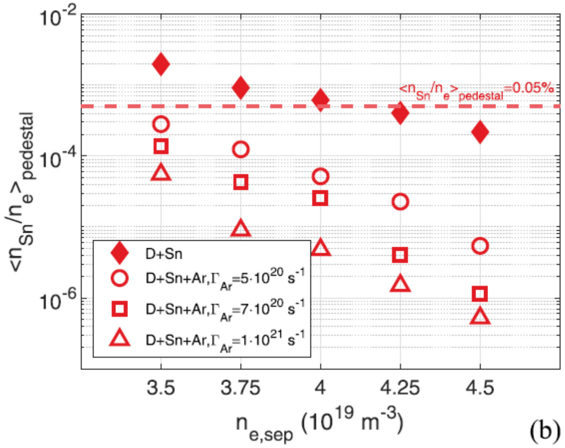


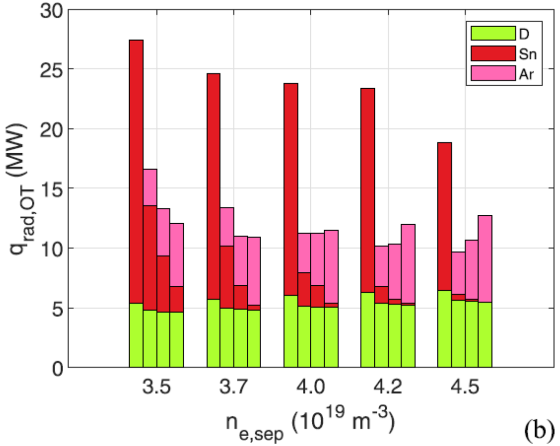
Modelling shows with Ar seeding core Sn concentration low and power to target acceptable (PoLiTo)

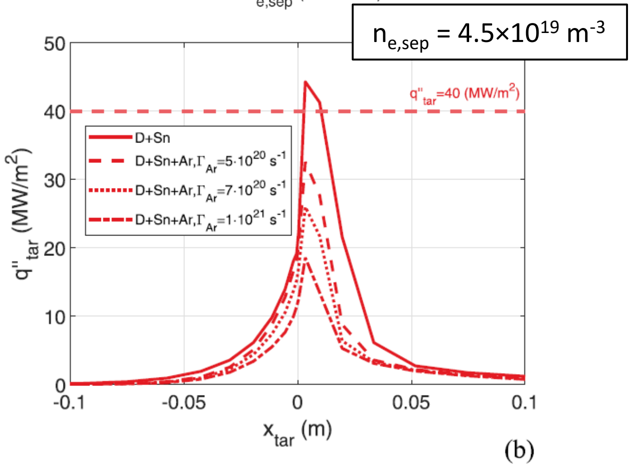


Addition of Sn reduces heat load, but Ar addition needed to radiate in SOL and lower core concentration level

With increasing Ar evaporation suppressed and Ar becomes dominant radiator in SOL



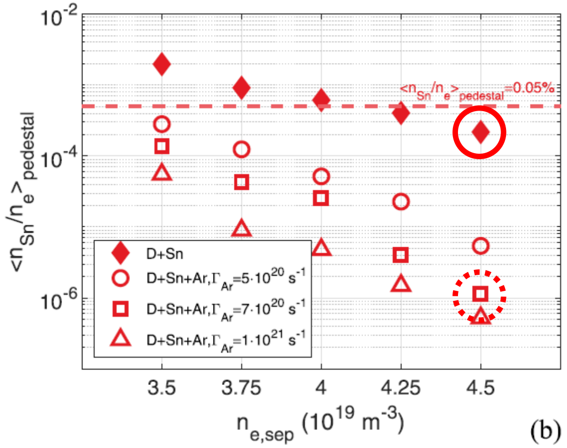


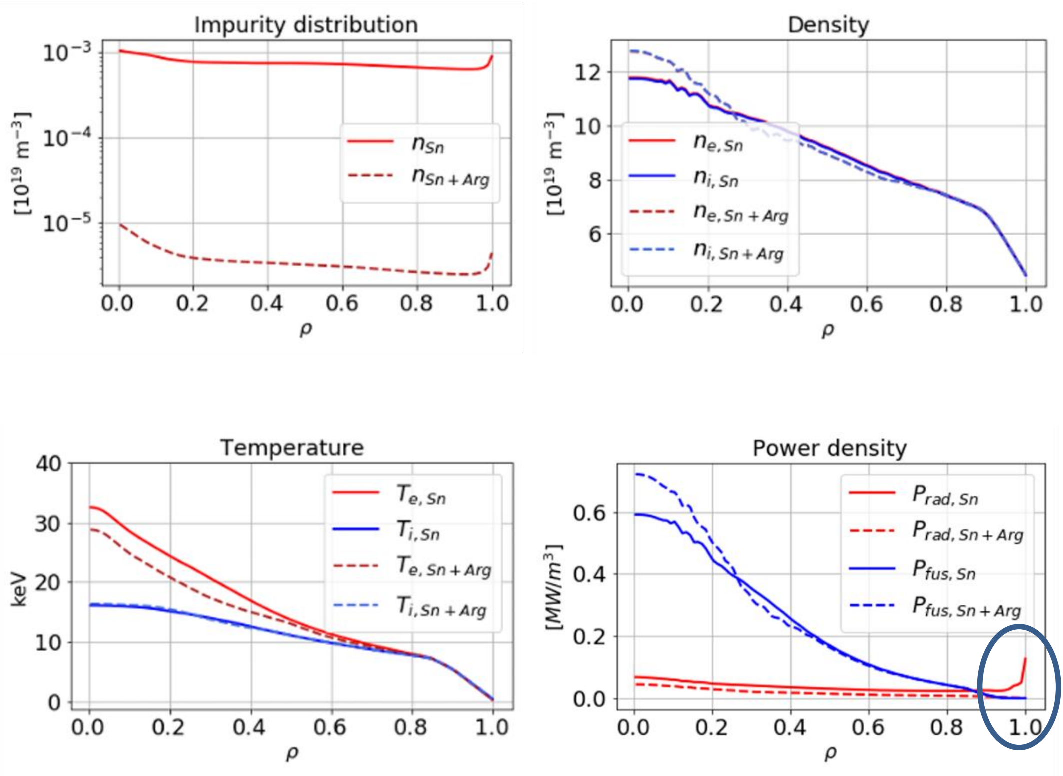


Nallo Nucl. Fusion (2022)

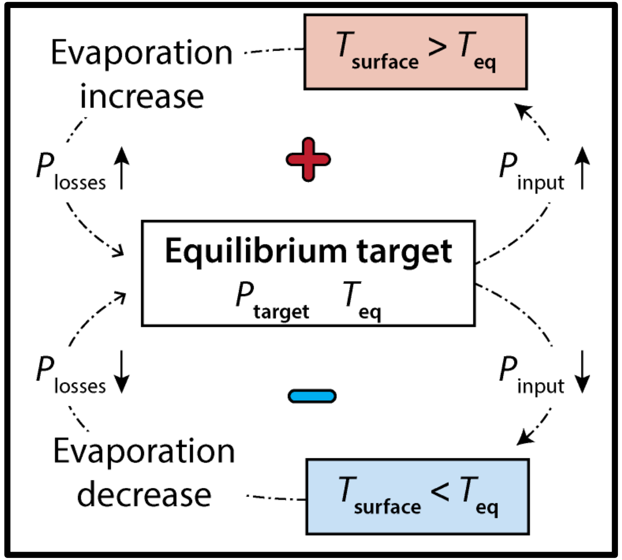
ASTRA results – Sn (PoLiTo)

DEMO scenario from SOLPS-ITER input to ASTRA code





Implications for operation



These results imply a self-stabilizing mechanism

For loss of detachment get temperature increase to point where Sn erosion will increase radiation. [Decrease in heat flux will lower Sn erosion and increase power to divertor surface]

Lead to automatic protection of divertor component (no damage)?

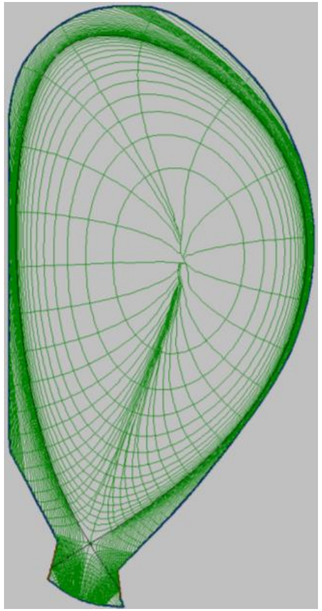
Divertor also may survive disruptions: less stringent limits for disruption mitigation? Same for ELMs?

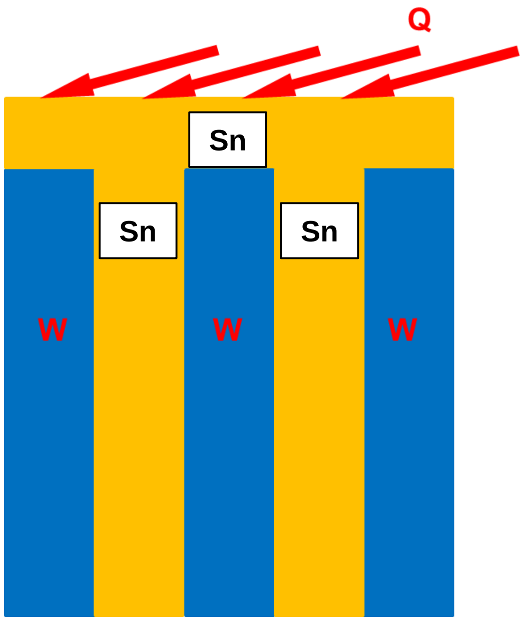
Can it better handle transient loads?

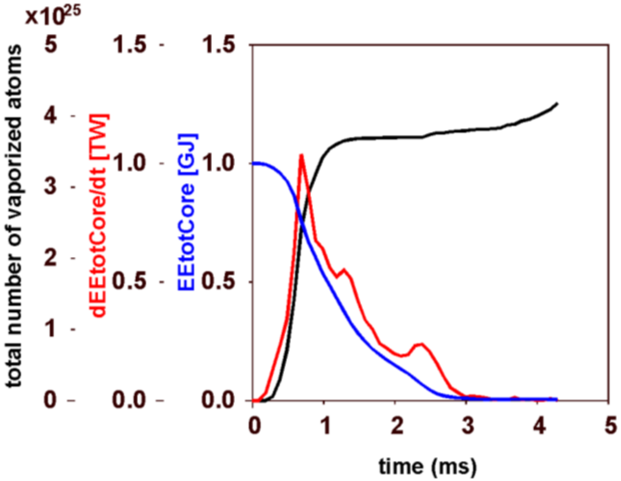
TOKES modelling used to investigate Sn CPS protection for divertor during disruptions (KIT)

1 GJ stored energy disruption in DEMO

Sn-based PFC on vertical targets, otherwise W

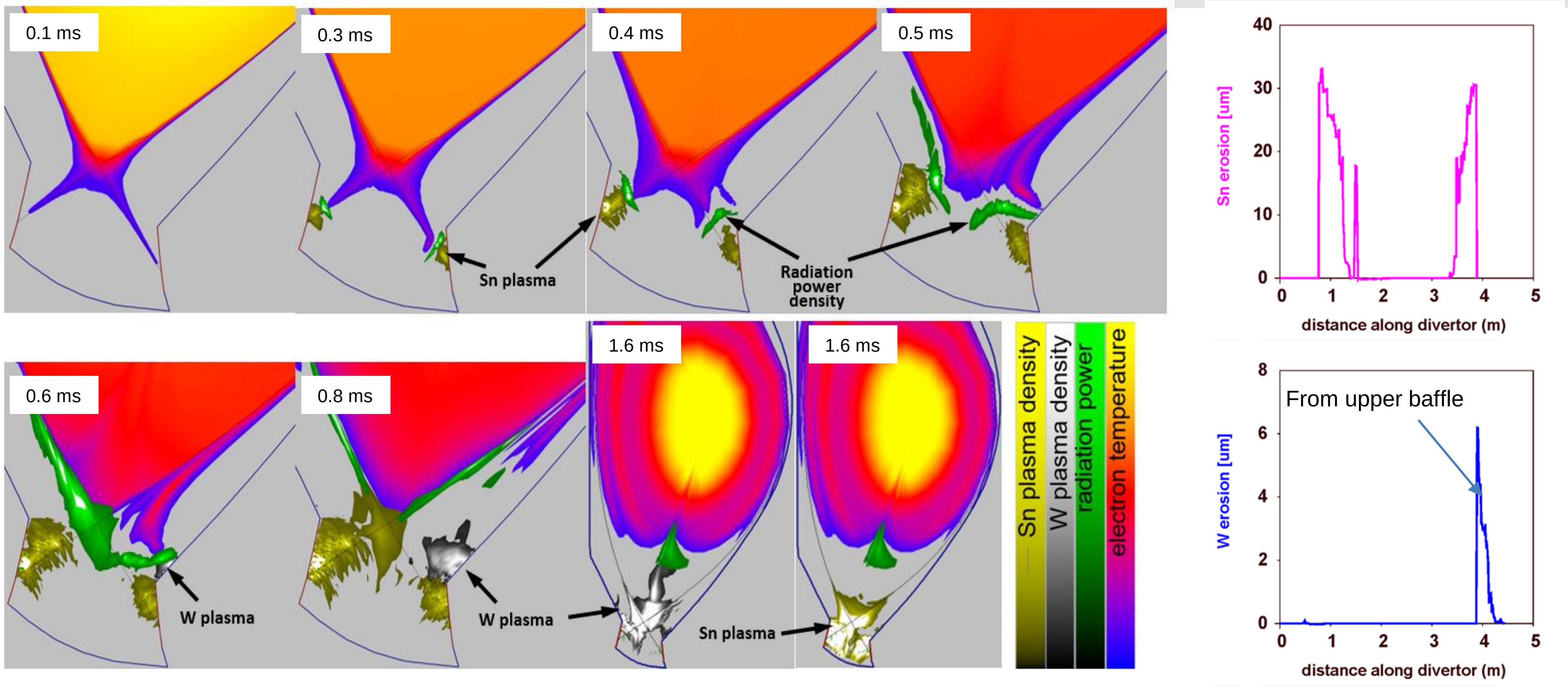






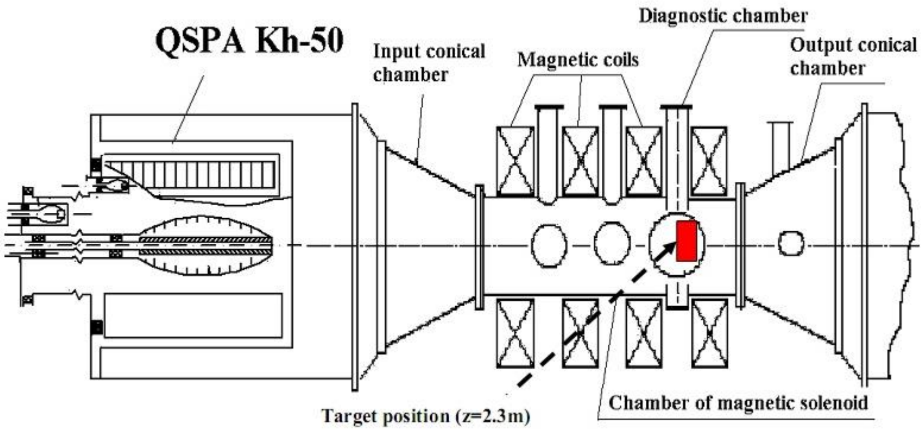
Courtesy Serguey Pestchanyi

TOKES modelling also shows Sn protection for divertor during disruptions (KIT)



Courtesy Serguey Pestchanyi

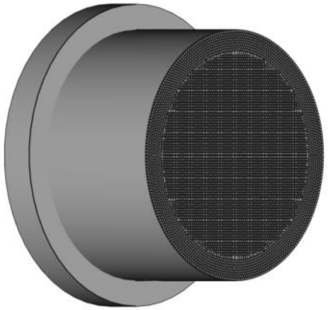
Experiments on QSPA Kh-50 explore how Sn-filled CPS performs under disruption-like loading (KIPT)



QSPA performance characteristics	
Energy density max	30 MJ/m^2
Pulse duration	0.25 ms
Pressure	3-18 bar
Electron density	0.2-5×10^{22} m^{-3}
B_0	0.54 T
Plasma diameter	15 cm

Makhlai Phys. Scr. (2021)

Test conditions	
Energy density	up to 3 MJ/m^2
Number of pulses	100
Base temperature	~ 300 °C , ~ RT

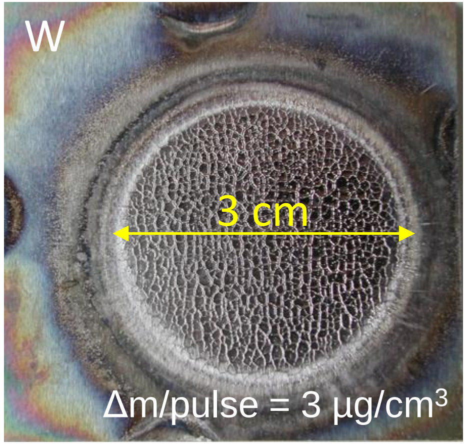


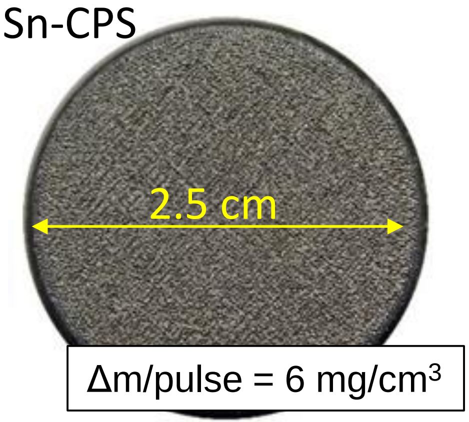
3D printed W CPS cylindrical samples of 25 mm in diameter and 17 mm in height were provided by Peter Rindt, DIFFER.

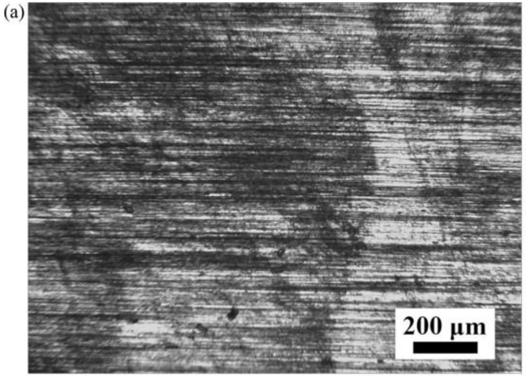
Rindt NF (2019)

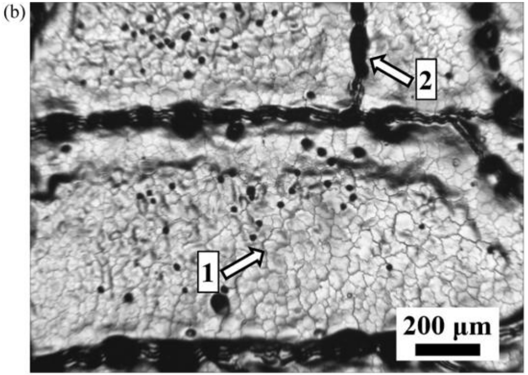
Comparison between Sn-CPS and W shows survival of CPS vs melting/cracking W (KIPT)

100 pulses @ 3 MJ/m^2 (>m.p. W)

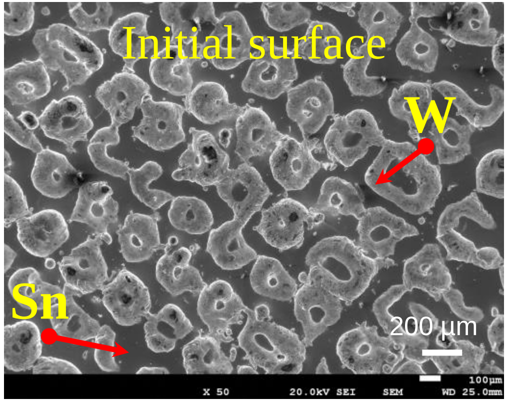


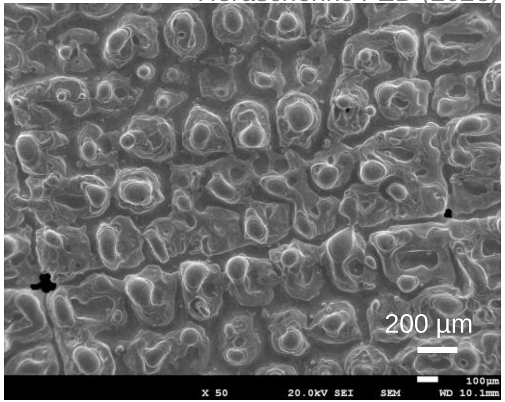






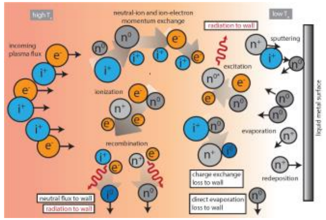
Makhlai NME (2019)
Heraschenko FED (2023)



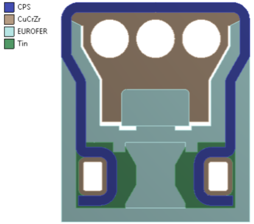


How to achieve a practical implementation?

Development path for a liquid metal divertor

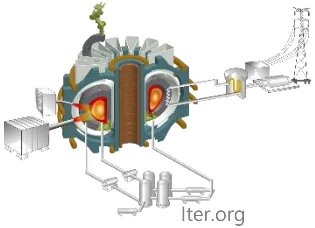


van Eden, PhD. Thesis , 2018



Rocella, JoFE (2020)

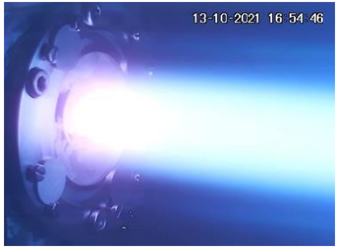
ipp.mpg.de

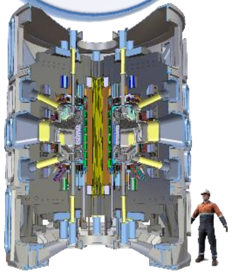


Iter.org

Physics basis → **Pre-conceptual design** → **Prototyping** → **Heat load testing** → **Tokamak small-scale testing** → **Tokamak large-scale testing** → **DEMO design**

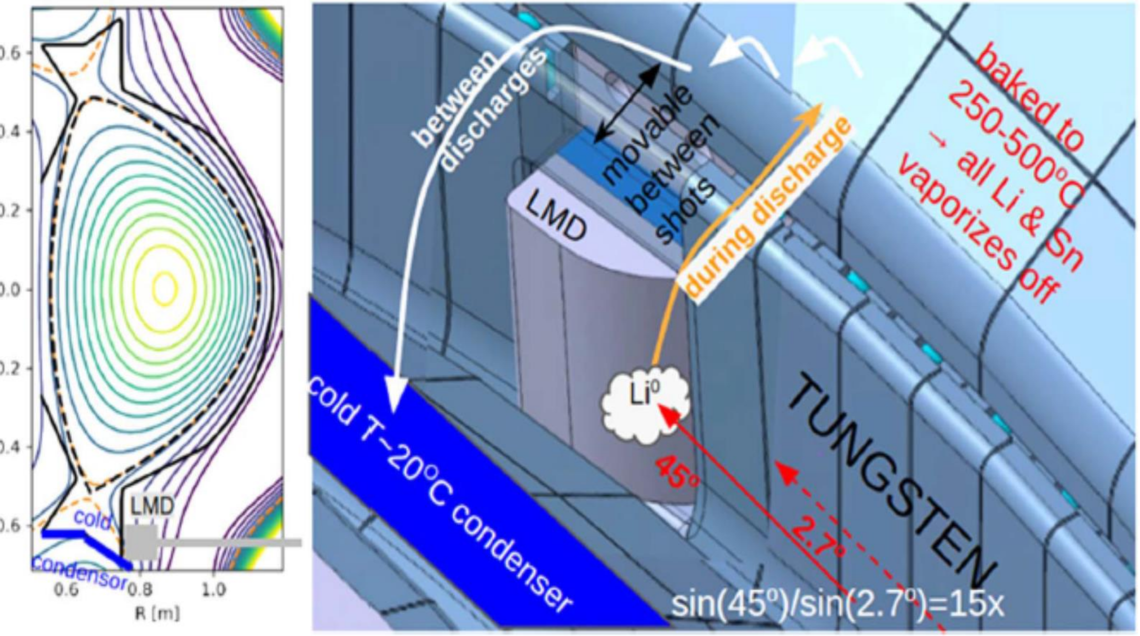
Rindt, NF (2019)





ipp.cas.cz

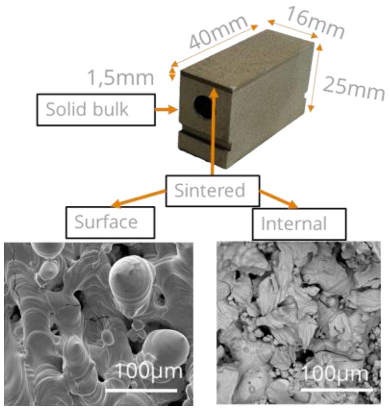
Stepping stone: COMPASS-U (IPP.CR)

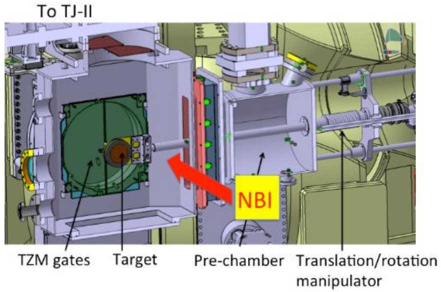


- Key near term device (late 2020s)
- High-field high current tokamak
- High density high heat flux divertor
- Inertially cooled PFCs (discharge 3s)
- Hot walls (300-500 °C)
- Divertor flexibility (install full toroidal ring)

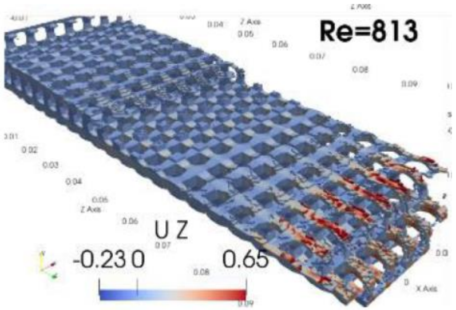
Courtesy R. Dejarnac

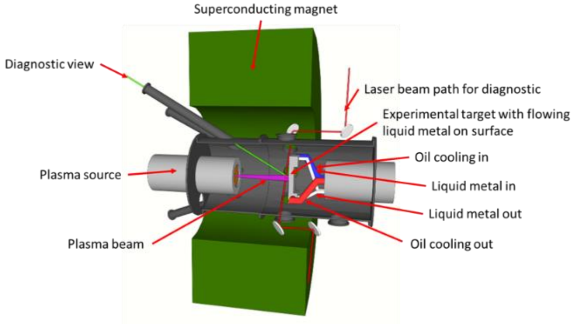
Activities towards implementation of development path





Activity
AUG experiment on Sn-CPS mock-up (DIFFER)
Magnum-PSI testing s.s. plasma loading (DIFFER)
OLMAT HHF loading (CIEMAT)
MHD flow modelling in CPS (UL)
COREDIV modelling of performance in COMPASS-U (IPPLM)
Corrosion barrier development (ENEA PoLiMo)
Spectroscopic data thermal sputtering Sn (CIEMAT)
Pre-conceptual design COMPASS test module (CCFE/IPP.CR)
Development optimized CPS design and prototype (DIFFER/ENEA/CCFE)
Development of new LM-dedicated linear plasma device LiMeS-PSI (DIFFER)



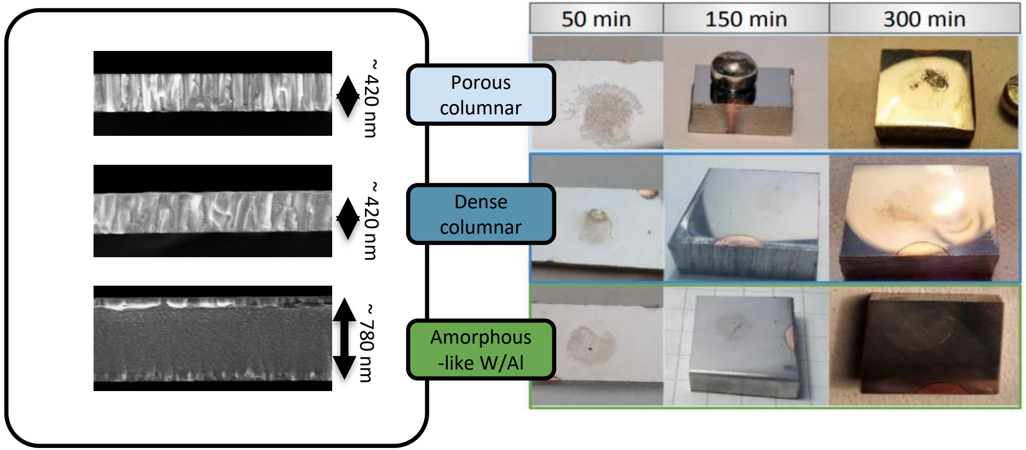


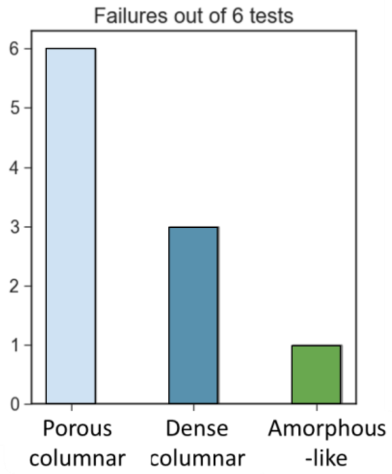
Example: corrosion barrier production (PoLiMo)

Sn corrosive for CuCrZr- may require protective barrier layer

W coatings prepared by HiPIMS and exposed to stagnant Sn droplet at 400 °C up to 5 hours

Initial studies show light element doped amorphous W structure most promising





Conclusions

Sn-based CPS divertor could provide resilient alternative for DEMO

Full conceptual designs indicate power handling up to 20 MW m^{-2} while strongly limiting Sn evaporation

With Ar seeding operational scenarios exist over a wide range of pedestal density compatible with core performance requirements

Natural negative feedback mechanism to stay in regime

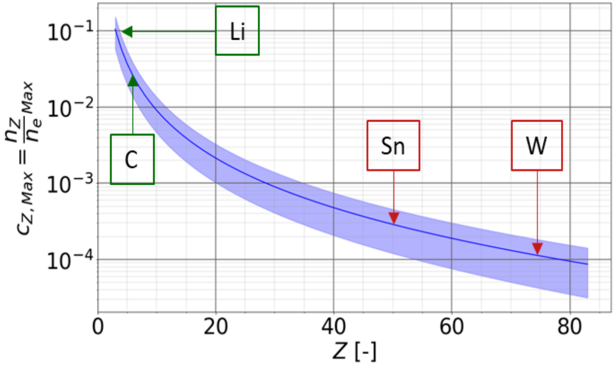
Modelling and experiments show survival against unmitigated disruption loads

Development of prototypes underway and new devices coming online to develop LMDs to next level

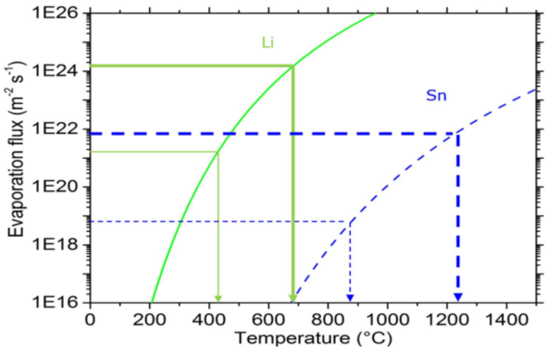
Material options of Li, Sn both have strengths and weaknesses

Choices once cost, availability, activation, material compatibility etc. taken into account

Lithium	Tin
Low Z	Higher Z
High vapour pressure	Lower vapour pressure
High T retention	Lower T retention



Putterich NF (2019)

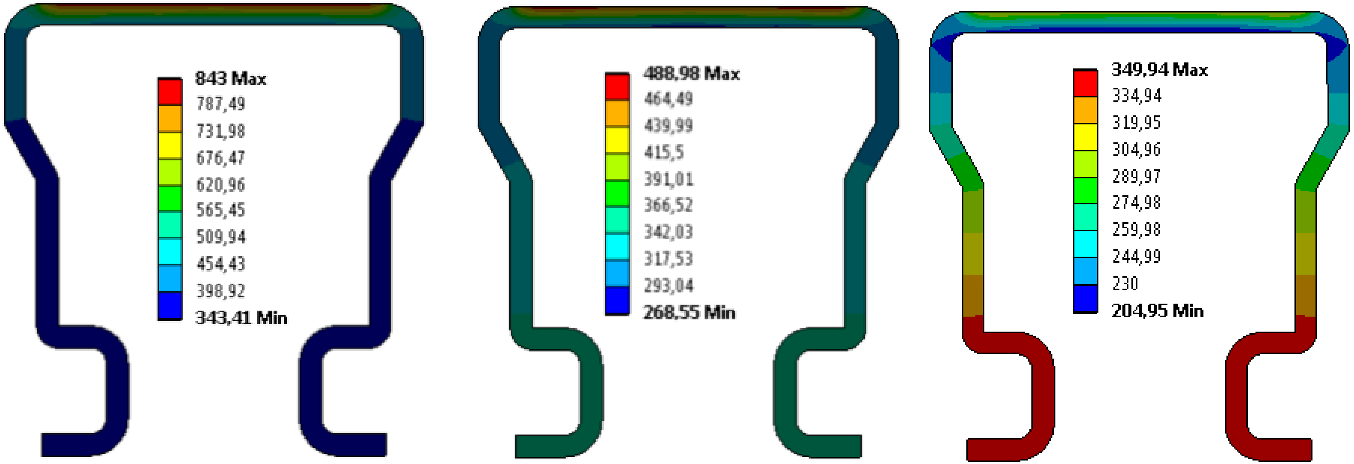


Morgan Plasma Phys. Control. Fusion (2018)

Sn-CPS based design most promising and mature technology

PFU thermal analysis (ENEA)

Heat flux = 20 MW/m^2 Heat flux = 10 MW/m^2 Heat flux = 5 MW/m^2

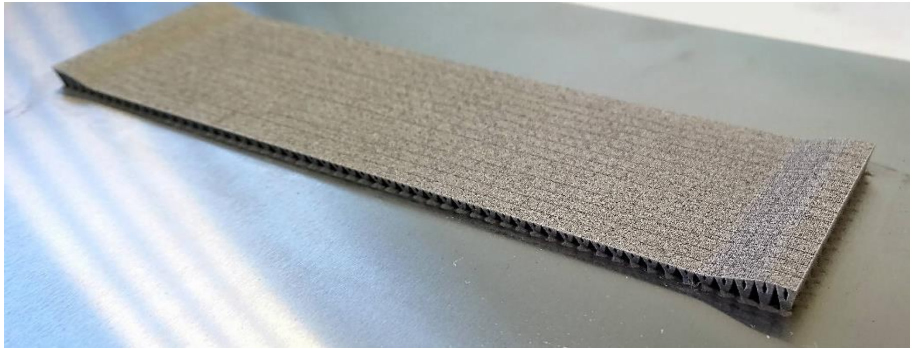


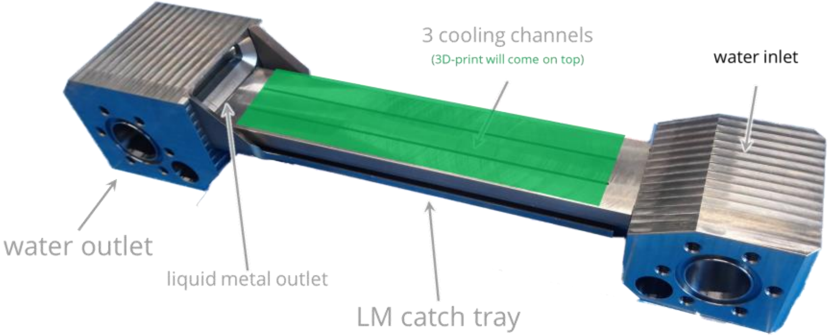
Roccella Journal of Fusion Energy (2020)

Tin is always liquid above 5 MW m^{-2}

Mock-ups being prepared for HHF testing (ENEA/DIFFER)

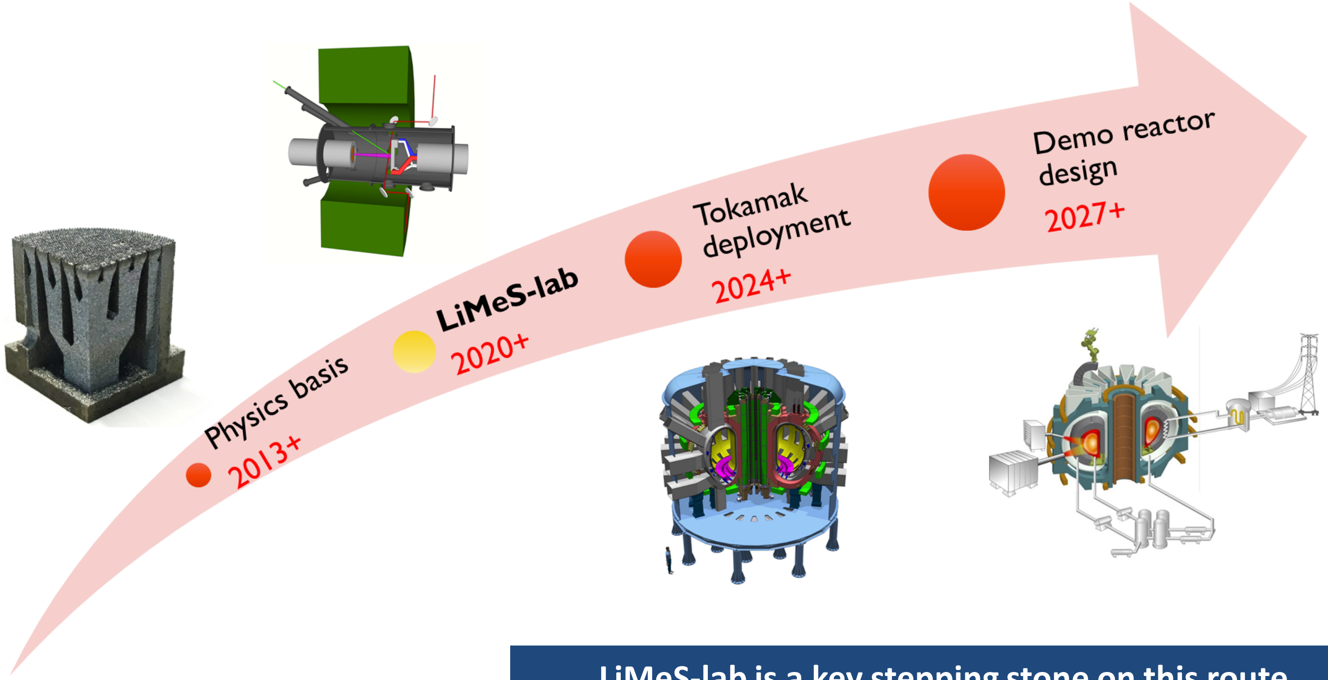
ENEA





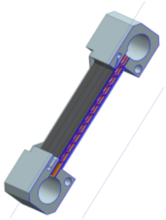
DIFFER

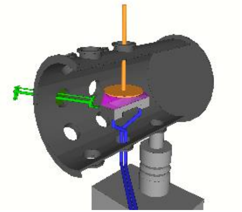
LiMeS-lab being constructed as an intermediate step to full development of LMDs (DIFFER)

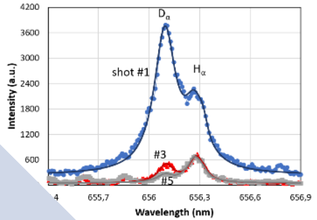


LiMeS-lab is a key stepping stone on this route

What is LiMeS-lab? (DIFFER)







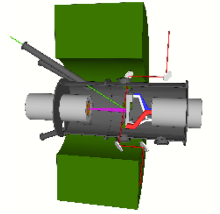
Design and manufacture mock-up

3D printing onto mock-up

Wetting liquid metal

Experiments linear plasma device

Post-mortem analysis

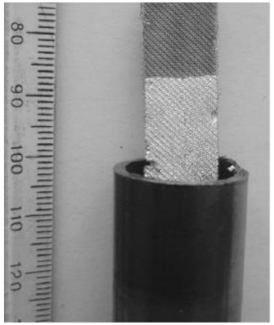


Approach Sn droplet production

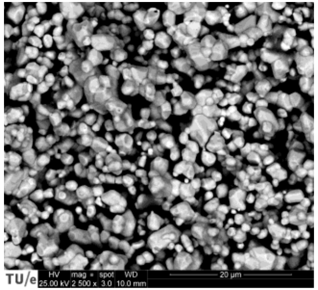
Screening testing using Magnum-PSI (high flux H plasma)

Pre-treatment by low flux plasma to remove oxides and improve wetting on W

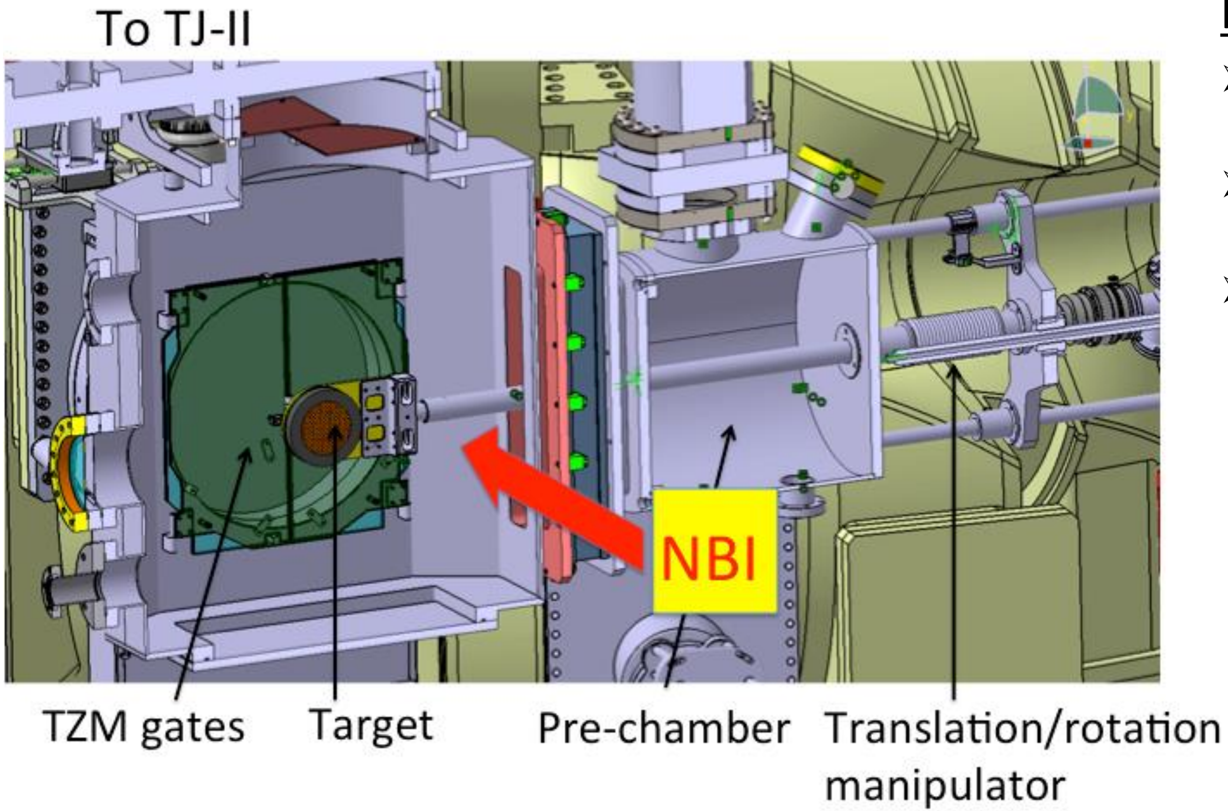
- ENEA felt (showed promising performance)
- Sintered surface 3D design
- Commercially sintered W
- 3D printed Mo sample
- Sn-Li sample



Surround targets with witness plates → RBS → determine Sn on plates
Fast image camera with Sn filter → see droplets
Optical emission spectroscopy → observe Sn emission evolution
Where possible embedded TCs, otherwise pyro IR → surface temperature

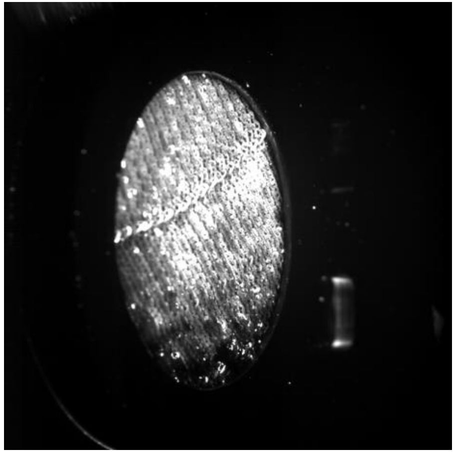


OLMAT facility designed for HHF neutral beam testing of LM targets (CIEMAT)



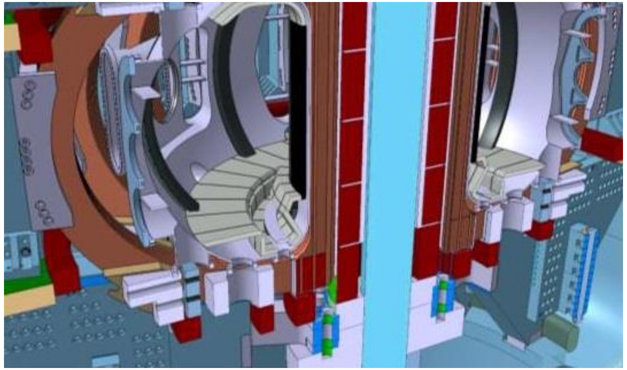
Performance:

- Maximum injected power: 705 kW → 50MW/m2
- Maximum pulse length: 150 ms (at medium power)
- Minimum pulse repetition rate: every 30 s.



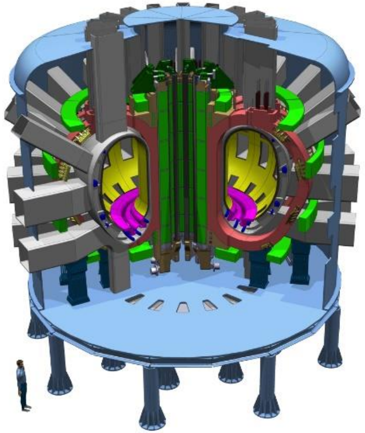
Long term: testing in COMPASS-U (IPPCR) and I-DTT (ENEA)

COMPASS-U (from 2025)



High field device
Closed high density divertor
High PB/R
Hot wall operation (300 ºC)
Flexible exchange of divertor possible

I-DTT (from 2027)



ITER-like divertor powers
DEMO-relevant PB/R
Divertor module exchange possible

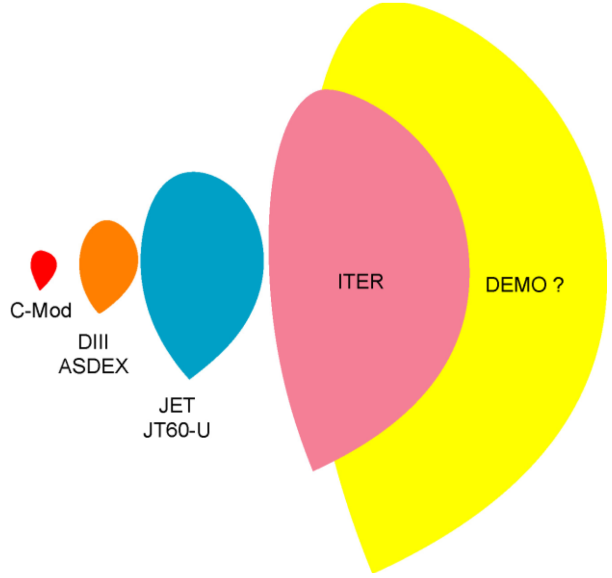
Conclusions 1/2

- LMDs are a promising alternative to W-based PFCs
  - Resilience to off-normal events
  - Greater lifetime
- Sn preferred to Li
  - T retention
  - Safety
  - Power handling
- Full conceptual designs indicate power handling up to 20 MW m^{-2} while strongly limiting Sn evaporation

Conclusions 2/2

- With Ar seeding operational scenarios exist over a wide range of pedestal density compatible with core performance requirements
  - Natural negative feedback mechanism to stay in regime
- Modelling and experiments show survival against unmitigated disruption loads
- Testing in AUG shows good survival but that improvements to understanding/design of CPS structures required
- Development of prototypes underway and new devices coming online to develop LMDs to next level

Going from ITER to DEMO involves large jumps in several parameters



Courtesy G. Matthews

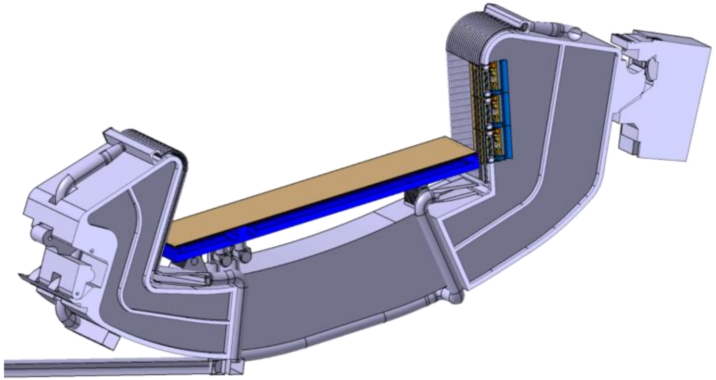
Property	ITER	DEMO[1]
Pulse length	~400 s	~7200 s
Duty cycle	**<2%**	**60-70%**
Neutron load	**0.05 dpa/yr**	**1-9 dpa/yr**
Exhaust power	150 MW	500 MW
Divertor area	~4 m^2	~6 m^2
Radiated power	**80%**	**97%**

Resilience to **neutrons** and **power excursions** on **long timescales** becomes more important

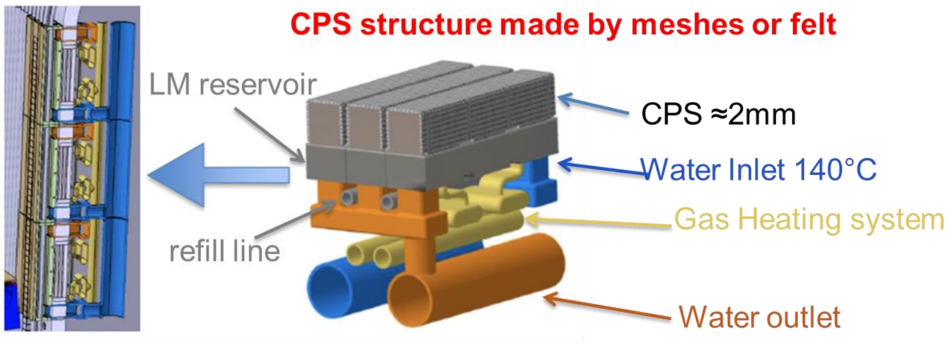
This is where **LM strengths** can play an important role compared to conventional solid divertor materials

[1]Wenninger NF (2017)

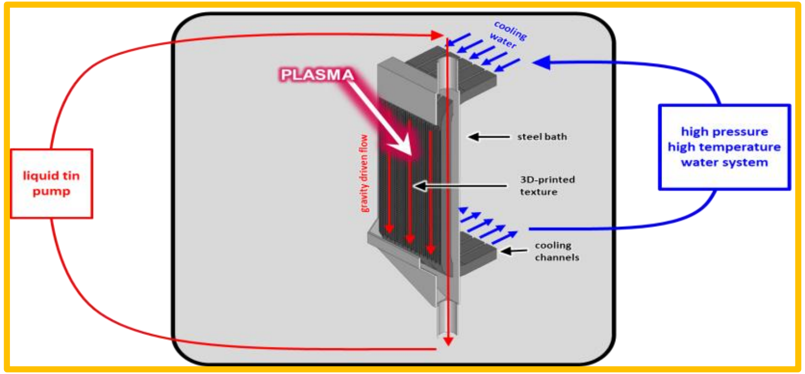
Several Sn-CPS based pre-conceptual designs have been developed (DIFFER/ENEA/CCFE)



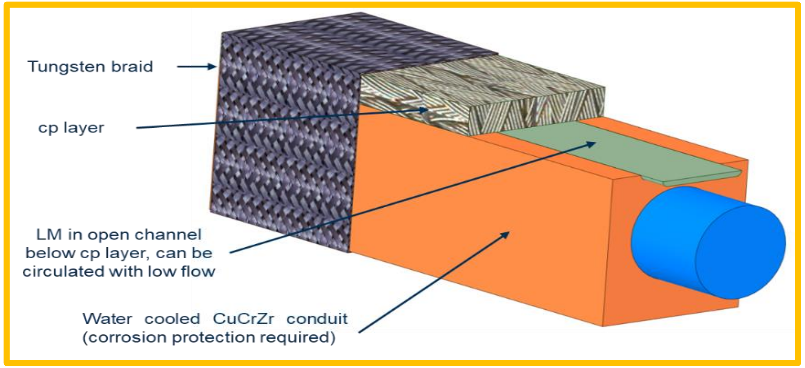
1. ENEA



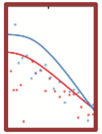
2. DIFFER



3. CCFE



ASTRA simulation strategy - overview



Initial conditions

Generic DEMO scenario [Siccinio et al., *FED* 2020]

- Safety factor, T_e, T_i, n_e profiles
- Auxiliary power

Boundary conditions

Outputs of SOLPS-ITER

- T_e, T_i, n_e, n_i, n_{D0}
- Γ of impurities

Interface set at separatrix (*)

(*) treatment of pedestal subject to improvements

ASTRA

$$\Gamma = -D\frac{\partial n}{\partial \rho} + V \cdot n \qquad q = \mathrm{X}\frac{\partial T}{\partial \rho} \cdot n$$

ASTRA computes the **main plasma transport equations**, evolving temperatures, densities and current, starting from initial and boundary conditions.

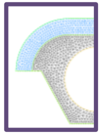
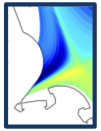
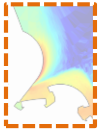
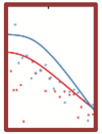
TGLF-NCLASS

The two codes implemented in *ASTRA*, evaluate **turbulent and neoclassical transport coefficients**, starting from the main plasma profiles

STRAHL

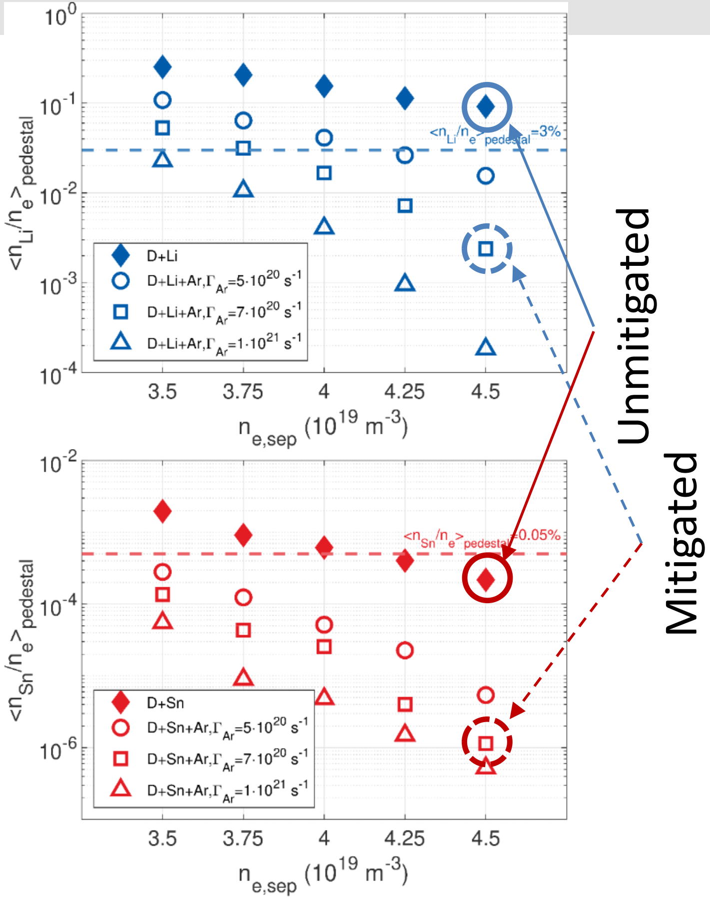
Computes the **impurity density profile** and the **radiated power**

ASTRA simulation setup

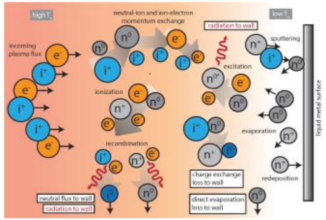





- Starting from database of SOLPS-ITER simulations [G.F. Nallo et al., Nucl. Fusion (2022)], consider one mitigated case and one unmitigated case for both Li and Sn (see figure)

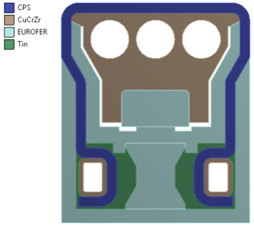
- More detailed overview on ASTRA setup:
  - B, I and $q(\rho)$ consistent with SOLPS-ITER simulations (EU-DEMO 2017 [5])
  - Boundary conditions from SOLPS-ITER imposed at separatrix ($\rho = 1$)
  - Profiles within pedestal ($0.85 < \rho < 1$) are not evolved
  - TGLF for turbulent transport includes TEM + ITG [6], NCLASS for neoclassical [7]
  - ASTRA evolved with one impurity (Ar neglected)
  - No resolution of individual charge states



Development path for a liquid metal divertor

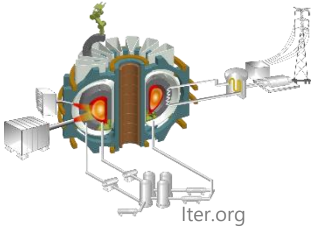


van Eden, PhD. Thesis , 2018



Rocella, JoFE (2020)

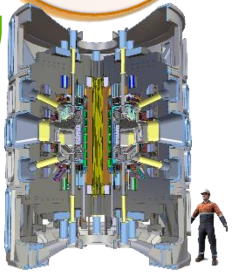
ipp.mpg.de



Iter.org

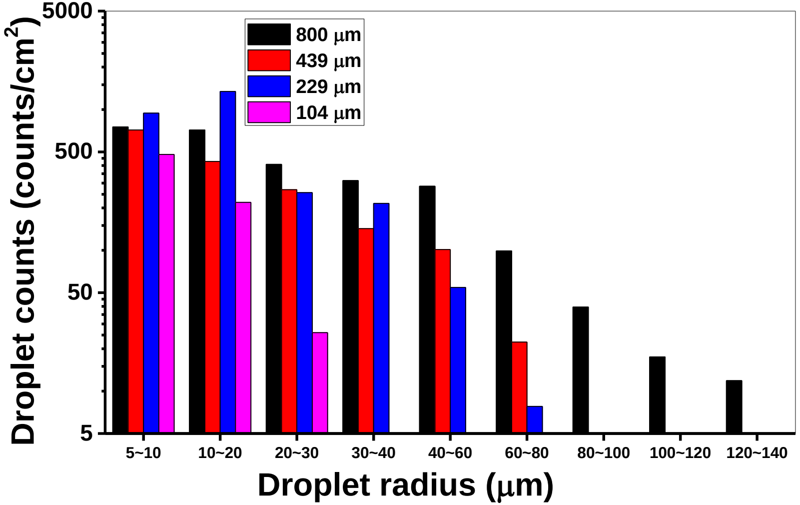
Physics basis → **Pre-conceptual design** → **Prototyping** → **Heat load testing** → **Tokamak small-scale testing** → **Tokamak large-scale testing** → **DEMO design**

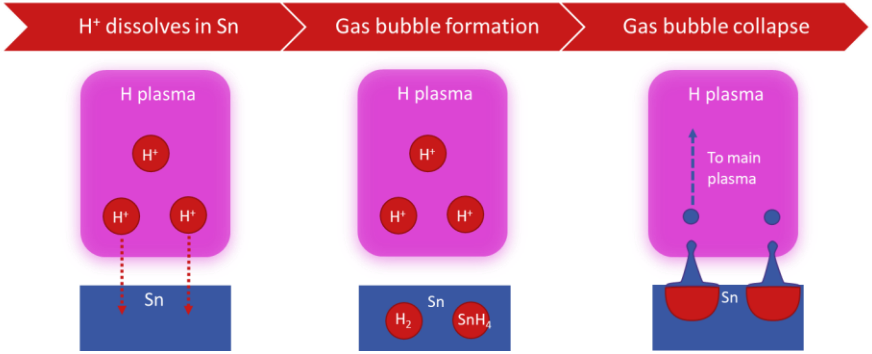
Rindt, NF (2019)



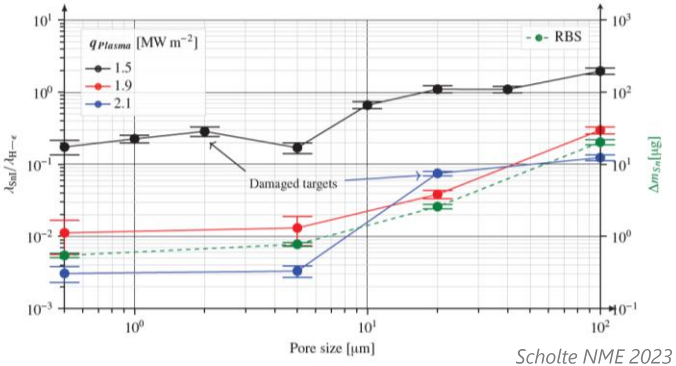
ipp.cas.cz

H atom/plasma flux can lead to Sn droplet formation. Can this be suppressed?





Ou NF 2020, Manhard NF 2020



Scholte NME 2023

Magnum-PSI experiment shows large reduction in Sn with pore diameter

Test setup for Sn bubble suppression

Clamping ring + Casing:

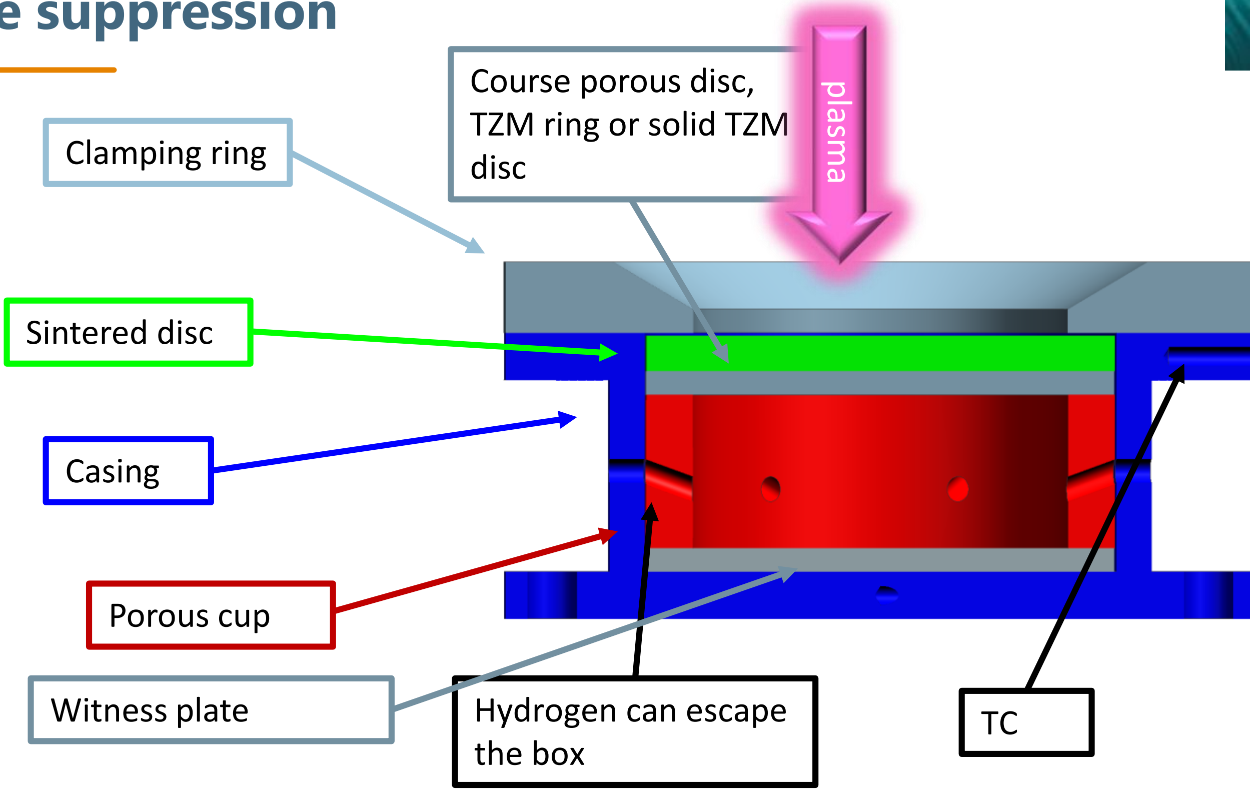
- Material: TZM
- Status: to me made

Sintered disc:

- Material: W
- Pore radius ≈ 1µm → S_C=90
- Status: ready and filled

Course porous disc and porous cup

- Material: ss (mottcorp), W (DUNLEE)
- Pore radius ≈ 20µm → S_C=20
- Status: to be made

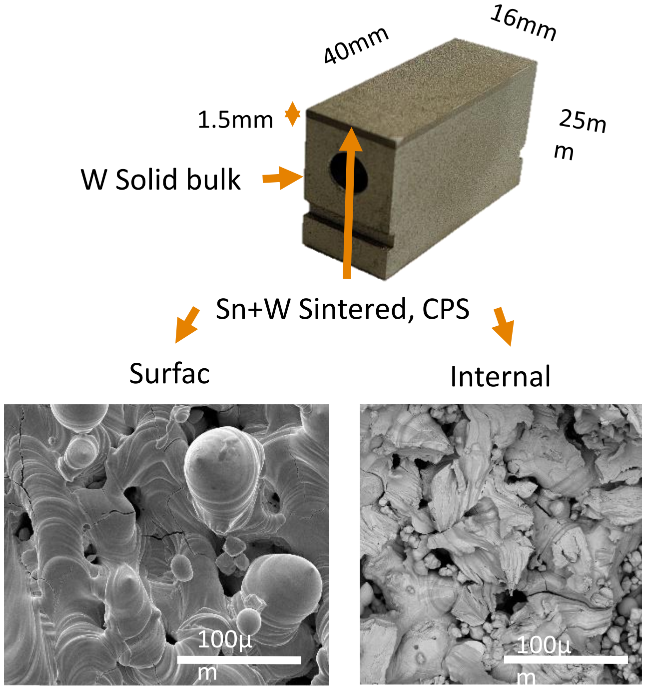


Design of the 3D-printed liquid tin module (LTM)

Design criteria:
1. Fit on the probe carrier
2. Maximum 2g Sn
3. Sn liquid start discharge

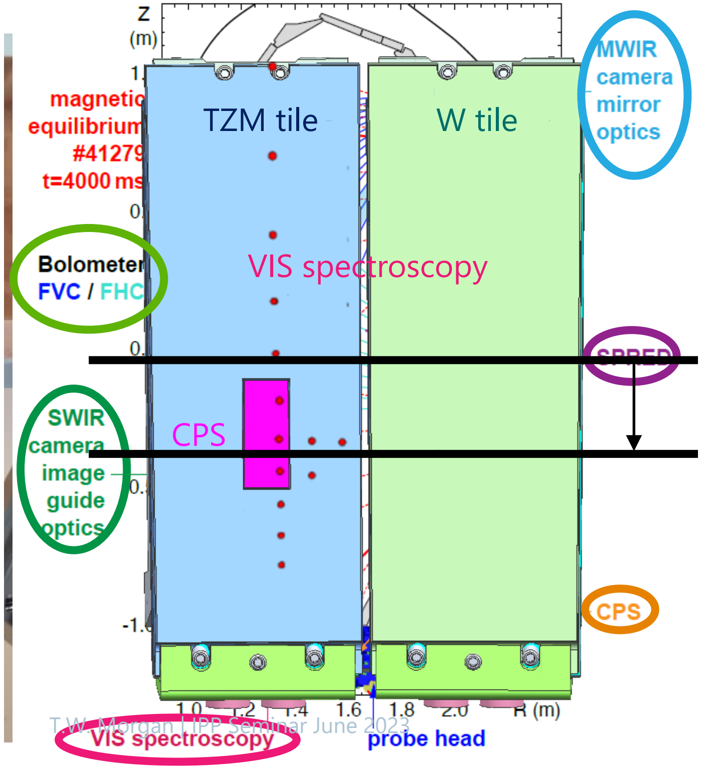
3D printing:
- Freedom design
- CPS attached to bulk
- Sintering small pore size (~50μm)

Pre-testing in GLADIS
- Thermal parameters validated vs FEM
- Limited Sn droplet ejection observed



Sintered CPS pore structure

CPS location, approach and diagnostics in ASDEX Upgrade



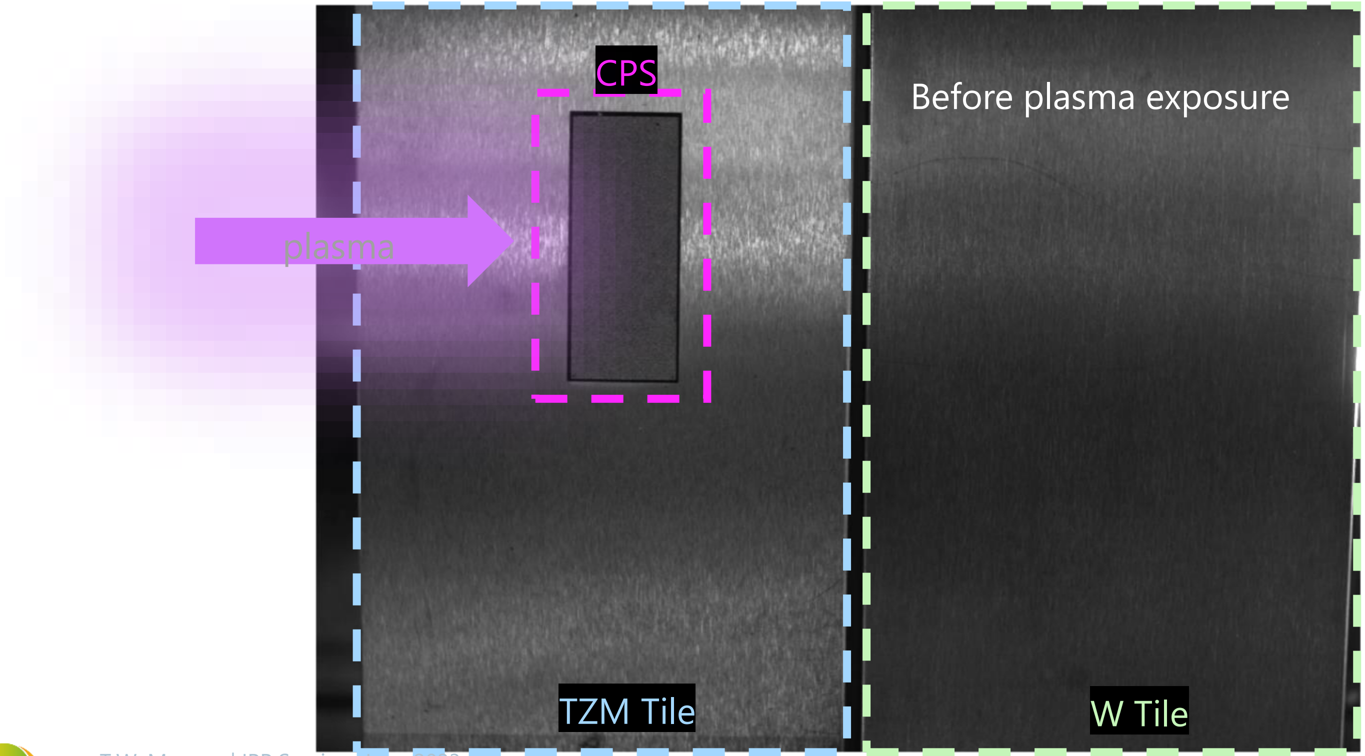
CPS mounted on divertor manipulator
- Flush-mounted insert into TZM tile
- Outer divertor vertical target
- **Strikepoint** moved down for fixed time

Local Sn gross erosion
- VIS spectroscopy lines of sight

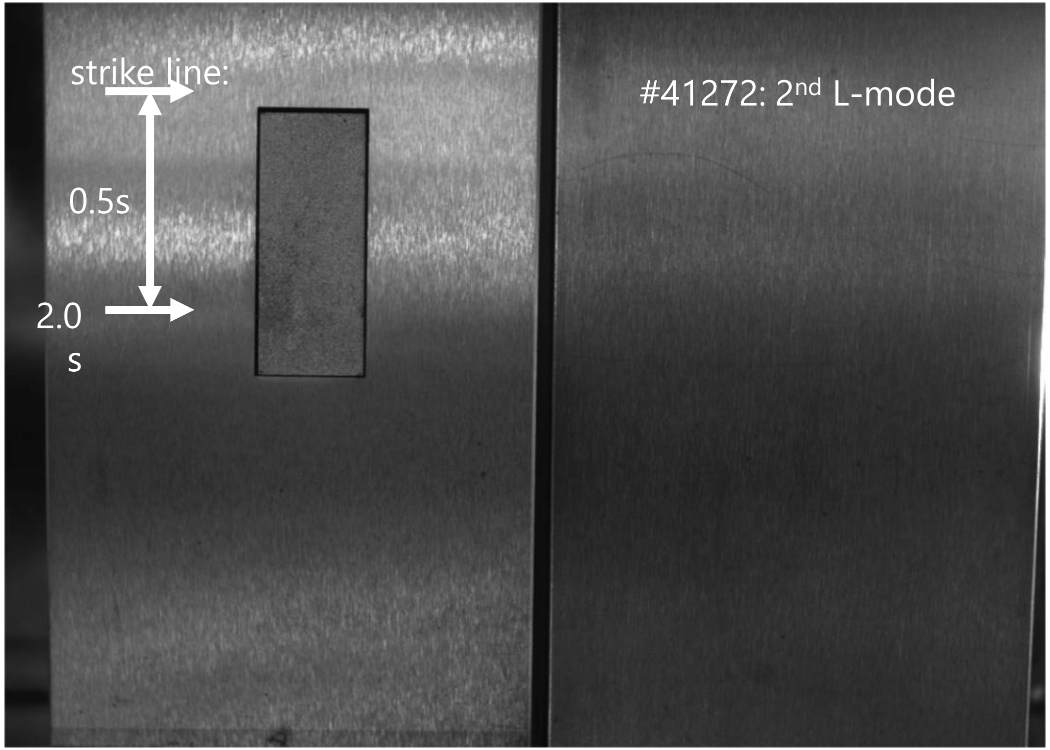
Temperature measurement
- 2 thermocouples inside CPS base block
- MWIR and SWIR cameras

Sn concentration in plasma core
- VUV spectrometer (SPRED)
- Main chamber bolometers

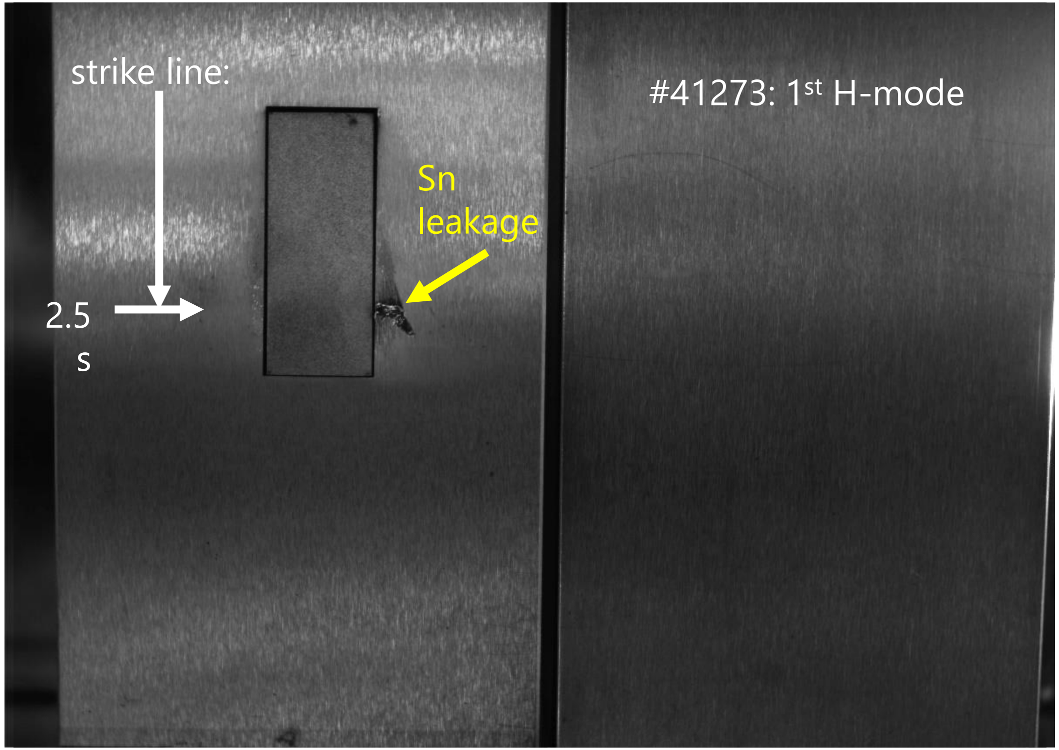
Evolution of the CPS during exposure: Before plasma exposure



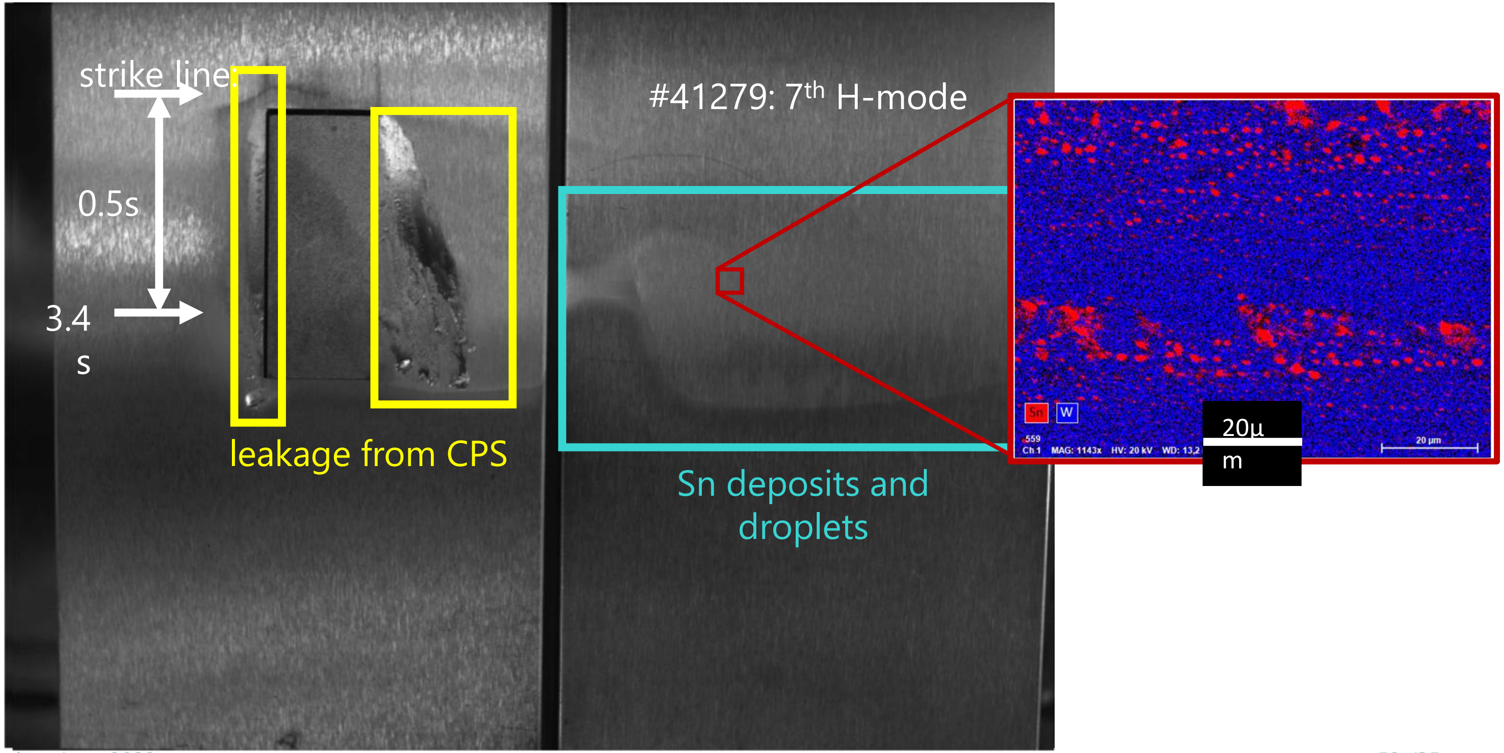
Evolution of the CPS during exposure: After 2nd L-mode shot



Evolution of the CPS during exposure: After 1st H-mode shot



Evolution of the CPS during exposure: After 7th H-mode shot



Strong Sn source observed when strike-line is on CPS

Divertor spectroscopy shows strong Sn I emission line (380.1 nm) once strike line is moved onto the CPS in H-mode

- Rough estimate of Sn gross erosion based on S/XB factor by Cremona et al.

  A. Cremona et al, Nucl. Mater. Energy 17 (2018) 253-258

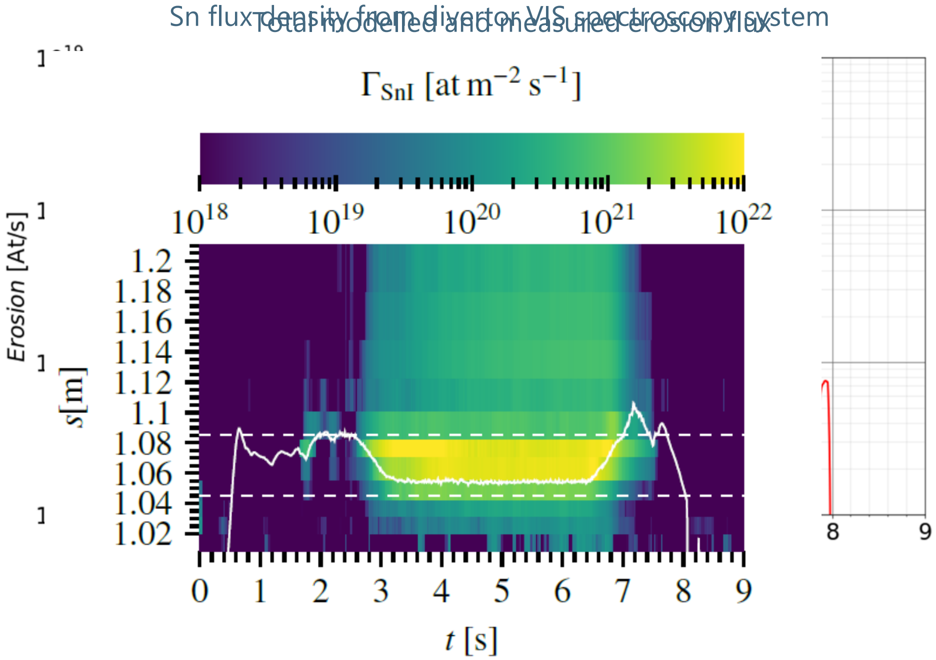
  ↘ *Divertor plasma hotter and denser than in Ref.!*

HeatLMD model underestimates Sn erosion

- Model considers sputtering & evaporation

  ↘ *Thermal sputtering expected to dominate*

- Discrepancy to experiment could be explained by Sn droplet emission



Sn core contamination beyond acceptable levels

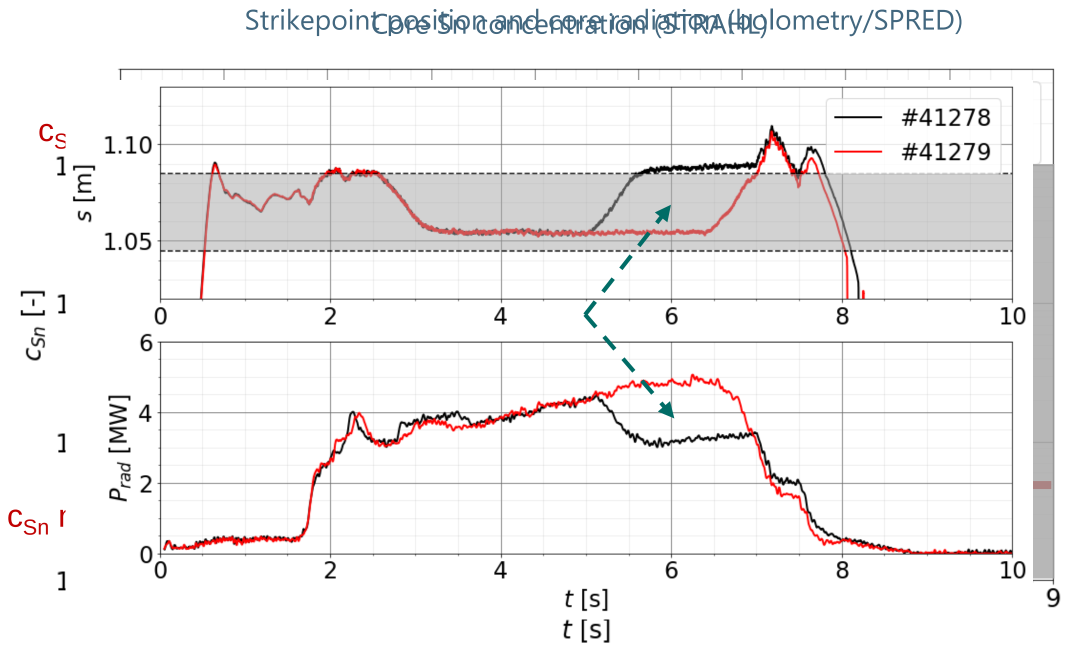
Total radiated power ~50% higher if strike line on CPS in H-mode

Using STRAHL model:

R. Dux (2006): STRAHL User Manual, Tech. Rep 10/30, IPP, Garching

- Estimate core Sn concentration $c_{Sn} = \frac{n_{Sn}}{n_e}$ from VUV spectroscopy
- CPS width was only ~1/650 of total divertor circumference!

based on: T. Pütterich et al, Nucl. Fusion **59 (2019) 056013 (assuming ρ* = 7.5)*



Causes of droplet production and consequences

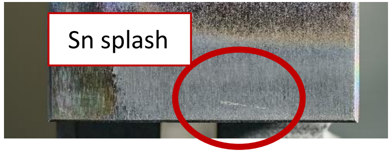
Droplet production source

- Leakage from open edge of CPS found
- Many small droplets found downstream
- Large splash ~0.5 m away found during scheduled opening

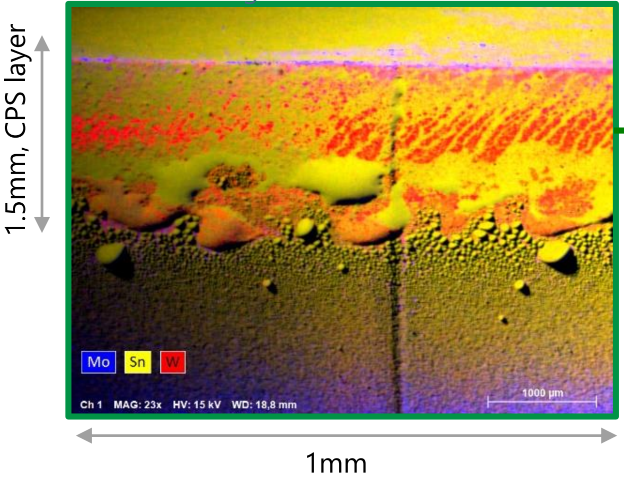
Causes of droplet production:

- Free surface Sn (leakage)
- Too large pore size?
- Poor wetting (oxides from air on bare W)?

Sector 1.3a tile post-opening



EDX image of side of TZM tile



TZM tile post-experiment

Conclusions for Sn use in DEMO

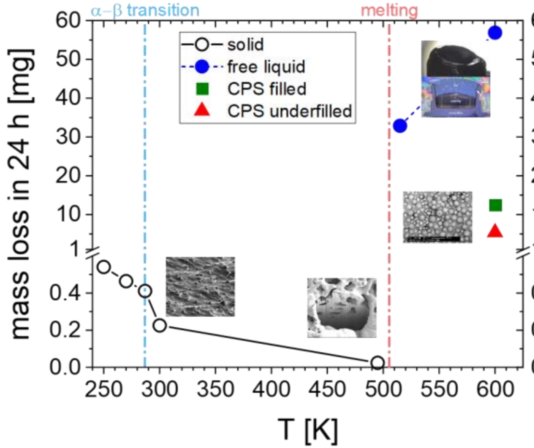
Control of Sn will be critical

- No **free surface** Sn allowed
- Likely need to reduce **pore size**
- Understanding and control of **wetting** vital

Other experiments indicate this is possible

More technology development required to demonstrate viability at lab/prototype scale before it could be considered for DEMO use

Summary of PlaQ Sn experiments



Manhard EPS conf. 2023

Nano-PSI exposure of CPS and free surface Sn