Liquid metal conceptual divertor designs for the European DEMO

T.W. Morgan¹, P.Rindt², N.J. Lopes Cardozo², R. De Luca³, G.Dose³, M.Iafrati³, A. Mancini³, G.Mazzitelli³, S.Roccella³, T. Barrett⁴, F. Domptail⁴, M. Fursdon⁴, D. Horsley⁴, D.Alegre⁵, E. Oyarzabal⁵, F.L.Tabares⁵, V.Pericoli Ridolfini⁶, Piotr Chmielewski⁶, I. Ivanova-Stanik⁶, M. Poradziński⁶, R. Zagórski⁶, R.Ambrosino⁷, F. Crisanti³ and B.E. Ghidersa⁹

¹DIFFER, The Netherlands; ²Eindhoven University of Technology, The Netherlands; ³ENEA, Italy; ⁴CCFE, United Kingdom; ⁵CIEMAT, Spain; ⁶Institute of Plasma Physics and Laser Microfusion, Poland; ⁷Consorzio CREATE, Italy; ⁸KIT, Germany
Going from ITER to DEMO involves large jumps in several parameters.

<table>
<thead>
<tr>
<th>Property</th>
<th>ITER</th>
<th>DEMO¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse length</td>
<td>~400 s</td>
<td>~7200 s</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>&lt;2%</td>
<td>60-70%</td>
</tr>
<tr>
<td>Neutron load</td>
<td>0.05 dpa/yr</td>
<td>1-9 dpa/yr</td>
</tr>
<tr>
<td>Exhaust power</td>
<td>150 MW</td>
<td>500 MW</td>
</tr>
<tr>
<td>Divertor area</td>
<td>~4 m²</td>
<td>~6 m³</td>
</tr>
<tr>
<td>Radiated power</td>
<td>80%</td>
<td>97%</td>
</tr>
</tbody>
</table>

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.

¹Wenninger NF 2017

Courtesy G. Matthews
Challenge for solid PFCs: avoiding component failure in DEMO

Need to avoid reaching component failure
- macrocracking leading to LOCA
- exceed CHF leading to melting
- fatigue failure
- Erosion limit

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

Planned replacement will require >6 months
Benefits of liquid metals for DEMO

Solid PFC:

- Sputtering
- Thermal shock/fatigue
- Big ELMs/VDEs/disruptions

LM PFC:

- Self replenishment
- No cracking
- Already molten

- Higher heat fluxes
- Lowered stresses substrate
- Vapour protection

ELMs possible(?)
Benefits of liquid metals for DEMO

**Solid PFC:**
- Sputtering

**LM PFC:**
- Self replenishment
- Higher heat fluxes
- No cracking
- Lowered stresses substrate
- ELMs possible (?)

**Neutrons**
- Thermal shock/fatigue
- Big ELMs/VDEs/disruptions
- Only influences substrate
- Separation of PSI from neutron issue

**Sputtering**
- Benefits of liquid metals for DEMO
  - Sputtering
  - Thermal shock/fatigue
  - Big ELMs/VDEs/disruptions

**Solid PFC:**
- Self replenishment
- Higher heat fluxes

**LM PFC:**
- No cracking
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- Benefits of liquid metals for DEMO
  - Sputtering
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**Solid PFC:**
- Self replenishment
- Higher heat fluxes

**LM PFC:**
- No cracking
- Lowered stresses substrate
- ELMs possible (?)

**Neutrons**
- Only influences substrate
- Separation of PSI from neutron issue
EU DEMO should have conceptual design completed by ~2027

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>NEAR TERM DEMO¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{fusion}}$</td>
<td>$2000\text{MW}<em>{\text{th}}/\sim500\text{ Mw}</em>{\text{e}}$</td>
</tr>
<tr>
<td>$\tau_{\text{burn}}$</td>
<td>2 hours</td>
</tr>
<tr>
<td>$R_0/a (\text{m})$</td>
<td>9.0/2.9</td>
</tr>
<tr>
<td>$P_{\text{sep}}$</td>
<td>153 MW</td>
</tr>
<tr>
<td>$P_{\text{sep}}/R_0$</td>
<td>17 MW m⁻¹</td>
</tr>
<tr>
<td>$I_{\text{plasma}}$</td>
<td>18 MA</td>
</tr>
<tr>
<td>$P_{\text{neutron}}$</td>
<td>1.04 MW m⁻²</td>
</tr>
<tr>
<td>$B_{\text{axis}}$</td>
<td>5.9 T</td>
</tr>
<tr>
<td>$W_{\text{plasma}}$</td>
<td>1.18 GJ</td>
</tr>
</tbody>
</table>

¹Federici FED 2018
EU LM strategy is risk mitigation: realistically should fit into DEMO design without huge changes to other components

1. Can fulfil all divertor requirements (heat/particle handling, ash removal)
2. Compliant with plasma (impurity) and scenario
3. Mountable in divertor cassette (remote maintenance)
4. Compliant with in vessel components, pumps, diagnostics…
5. Something that can relatively easily be incorporated into Engineering design after decision point ~2027

Basic assumptions:
- want to use **most mature technology**, CPS
- **Cooling by conduction** to coolant
Description of WP (2018-2019)

- Develop conceptual designs
- Integrate with rest of plant
- Assess power handling capability
- Influence of LM erosion on plasma performance
- Stabilization of LM surfaces by porous media
- Material compatibility in terms of wetting, corrosion, embrittlement
- LM fuel retention
- Safety precautions
Material options of Li, Sn both have strengths and weaknesses

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

<table>
<thead>
<tr>
<th>Lithium</th>
<th>Tin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Z</td>
<td>Higher Z</td>
</tr>
<tr>
<td>High vapour pressure</td>
<td>Lower vapour pressure</td>
</tr>
<tr>
<td>High T retention</td>
<td>Lower T retention</td>
</tr>
</tbody>
</table>

Need to develop design criteria to specify leading option
## Design criteria: performance

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

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

Tritium inventory control with Li requires continual active removal
## Design criteria: compatibility

<table>
<thead>
<tr>
<th>Design requirement</th>
<th>Sn</th>
<th>Li</th>
</tr>
</thead>
<tbody>
<tr>
<td>High recycling divertor</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>Activation must be kept to limits for intermediate level waste</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Lifetime 2 fpy</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>70 cm high vertical target</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Need to be able to re-wet in-situ</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Withstand atmosphere for 2 months during maintenance</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>Withstand 200 °C bake during startup</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>No major design changes to in-vessel components, diagnostics, first wall</td>
<td>✓</td>
<td>x</td>
</tr>
</tbody>
</table>

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

Long term Li may be better [see next talk] but technologically much more complex

**Sn chosen as candidate LM for this application**
Several Sn-CPS based pre-conceptual designs being developed
All designs capable of normal operation up to $\sim 20 \text{ MW m}^{-2}$

Using CPS means component can be significantly thinned compared to W monoblock design

Possible to keep temperature below range where evaporation becomes significant
Critical heat flux is operational limit

Can keep temperature of Sn below point where evaporation becomes an issue

Main failure mode is therefore reaching CHF leading to severe reduction in heat transfer coefficient

\[ q = h(T_w - T_{sat}) \]

Some definitions:
- Peaking factor: \( f_p = \frac{q_w}{q_0} \)
- Incident CHF: \( ICHF = \frac{CHF}{f_p} \)
- CHF Margin: \( MCHF = \frac{ICHF}{CHF} \)
Different design choices give different trade-offs: need to optimize

<table>
<thead>
<tr>
<th>Design choice</th>
<th>ENEA</th>
<th>DIFFER</th>
<th>CCFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid metal</td>
<td>Sn</td>
<td>Sn</td>
<td>Sn</td>
</tr>
<tr>
<td>CPS type (2 mm thick)</td>
<td>Mesh/felt</td>
<td>3D printed</td>
<td>Braid</td>
</tr>
<tr>
<td>Sn resupply</td>
<td>Capillary reservoir</td>
<td>Capillary/flow</td>
<td>Capillary reservoir</td>
</tr>
<tr>
<td>CPS max pore size (µm)</td>
<td>50</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Water temperature*</td>
<td>120 °C</td>
<td>180 °C</td>
<td>240 °C</td>
</tr>
<tr>
<td>Water pressure (bar)*</td>
<td>50</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Water flow rate (m s⁻¹)*</td>
<td>12</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Sn liquid?</td>
<td>&gt;5 MW m⁻²</td>
<td>During operation</td>
<td>Always</td>
</tr>
<tr>
<td>ICHF (MW m⁻²)*</td>
<td>33</td>
<td>56</td>
<td>25</td>
</tr>
<tr>
<td>MCHF</td>
<td>1.65</td>
<td>2.8</td>
<td>1.25</td>
</tr>
<tr>
<td>Sn heating</td>
<td>Gas in PFC</td>
<td>Gas in cassette</td>
<td>Water</td>
</tr>
</tbody>
</table>

*Note: *c.f. DEMO ITER-like PFC: 140 °C, 50 bar, 14 m s⁻¹, ICHF=45 MW m⁻², MCHF=1.4
Example design: DIFFER cross section single pipe row

CPS thin enough to get low surface temperature during nominal operation, but thick enough that VS occurs during transients (avoid reaching CHF)

W/Cu composite has higher strength at high temperature (development WPMAT)

Only W faces Sn: no corrosion

Coolant is compromise between keeping surface cool and Sn liquid

No monoblocks (alignment issues), only rows of pipes
Performance analysis shows normal performance up to 24 MW m\(^{-2}\) possible with target damage only at 56 MW m\(^{-2}\)

Normal operation up to 24 MW m\(^{-2}\) before onset nucleate boiling (slow transient only)

This is well below Sn evaporation limit defined

Target only damaged at 56 MW m\(^{-2}\) due to CHF reached

At 23.8 MW m\(^{-2}\) this becomes the limiting factor (only allowed during off normal events)
Von mises stresses are low in pipe even up to CHF so can operate in slow transients up to 56 MW m⁻²

Stresses well below UTS of W/Cu composite (500 MPa at 816 °C)

Real failure point is yield stress however (unknown as yet)

Given safety margin operational limit during slow transients should be 43 MW m⁻²
Disruptions can be survived without damage if significant vapour shielding occurs

Apply 80 MW m$^{-2}$ 4 ms disruption to FEM including VS model

Failure mode is W melting point

Given reasonable assumptions for $\epsilon_{\text{cool}}$ and $R$ find that disruptions are survivable without damage

Similar for big ELMs

Don’t need to worry about CHF, time too short

$$Q_{\text{plasma}} = Q_{\text{cond}}\left(T_{\text{surf}}\right) + (1 - R)\Gamma_{\text{evap}}\left(T_{\text{surf}}\right) \cdot (\epsilon_{\text{cool}} + \epsilon_{\text{col}} + \epsilon_{\text{evap}})$$
Implications for operation

For loss of detachment get temperature increase to point where Sn evaporation will decrease fusion power in core

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

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

Risk of radiative collapse or negative feedback mechanism to avoid it?
Core compatibility: COREDIV

COREDIV = 1D transport in the core self-consistently coupled to 2D model in the SOL
Aims at steady state description of plasmas with impurities

The energy balance

1D core

2D SOL

- \( P_{\text{ECRH}} \)
- \( P_{\Omega} \)
- \( P_{\text{NBI}} \)
- \( P_{\text{ICRH}} \)

\( P_{\text{fus}} \)

\( P_{\text{rad}} \)

Kinetic energy electrons

Kinetic energy ions

Energy exchange
\( Q_{ei} \propto v_e (T_e - T_i) \)

Boundary conditions: \( n_i, n_z, T_e, T_i \) – from SOL model
\( P_{\text{inp}}, G_{\text{inp}} \) – calculated from core model

Advantages:
- short running time (~one day)
- Impurity modeling, including radiation in the core and in the SOL and therefore possible assessment of the heat load to the target.

Drawbacks:
- SOL slab geometry
- Semi-analytical model of neutrals

Target: sputtering, evaporation

\( \propto \kappa_e \nabla T_e \)

conduction

\( \propto \kappa_i \nabla T_i \)

convection

neutral flux

cx hot neutrals

Impurities

LM conceptual design for EU DEMO  T.W. Morgan | IAEA Divertor concepts | Vienna | Nov 2019  21/27
COREDIV handling of LM impurities

At divertor surface evaporation and sputtering sources coupled to incoming heat and particle flux.

Radiation in core modelled using coronal curves.

Source scanned by varying $d_{\text{Sn}}$, $d_{\text{W}}$ or $T_{\text{cool}}$.

Use of Sn can be compatible with good core performance using Ar seeding

Seeding Ar increases SOL radiation and lowers core radiation by reducing Sn source

Can operate above L-H threshold while also detached at target plate

Similar scenario to W target with Ar or Ne seeding (Q=34-36) [Ivanova-Stanik J. Nucl. Mater. (2015)]

n.b. deliberate scenario with v. high Sn source ($d_{Sn} = 2$ mm, $d_W = 50$ mm, $T_{cool} = 500 \ ^\circ$C, $T_{surf} \sim 2000 \ ^\circ$C)
TECXY has also been used to study the effect of Sn on performance

2D multifluid description— Braginskij like equations simultaneous treatment of few impurity species

Classical parallel transport

Radial Transport: several options – constant diffusion coefficients, Alcator-like, turbulent transport

2 Temperatures Model (Te and Ti) all ions same Ti

Atomic processes: ionization, recombination, excitation, charge exchange (Li, Be, B, C, O, Ne, Ar, Si, Ni, Sn, Mo)

Neutrals (analytical & fluid model for neutrals): hydrogen recycling, impurity sputtering and EVAPORATION

Curvilinear tokamak geometry
Similar conclusions reached that with seeding impurities good performance achieved (modelling for I-DTT but similar for DEMO)

Again high Sn source conditions chosen ($d_{Sn} = 1 \text{ mm}, d_{W} = 7 \text{ mm}, T_{cool} = 700 \degree \text{C}$)

High density scenarios result in detachment and low core impurity even without seeding

Even at low density addition of seeding impurity leads to reduction of power at plate while keeping plasma dilution low
Next steps

Development of prototypes based on pre-conceptual designs

Testing in plasma and heat load devices

Magnum-PSI

OLMAT

QSPA-Kh50

Plasma/ELMs

Heat loads

ELMs/disruptions
Conclusions

DEMO heat exhaust challenges can be addressed using a Sn-CPS based divertor solution

A 20 MW m\(^{-2}\) steady-state heat load can be sustained while maintaining good core performance

Development and testing of prototypes is ongoing as a step towards deployment in confinement devices to demonstrate these benefits