Low-recycling liquid-metal ‘divertorlets’ concept for heat exhaust in divertors of fusion reactors

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Motivation

Divertors experience heat loads. Solid plasma-facing components are limited. Liquid metals (LM) can carry away heat and self-heal through replenishment.However, there is no consensus on the most advantageous configuration. Flow speed |**U**| is one critical parameter since MHD drag~|**U**|. Fast flows have risk of piling/splashing. Slow flows may not avoid evaporation [2-3].

The Divertorlets Concept

- Advantages of fast and slow flows: low MHD drag and reduced exposure time to the plasma.
- Mixing of the bulk liquid metal to handle greater heat loads.
- **Temperature below 450°C** for liquid Li.
- Continual flow mixing ensures a constantly fresh plasma-facing surface: **low hydrogen recycling.**
- Directionally alternating flow paths in channels, separated by ‘slats’ (Fig. 3).
    - External current generates a current distribution **j** by conductors in every other channel. With a tiroidal field **B**, **j**×**B** drives the pressure difference between channels, and drives the flow due to the designed slat geometry.

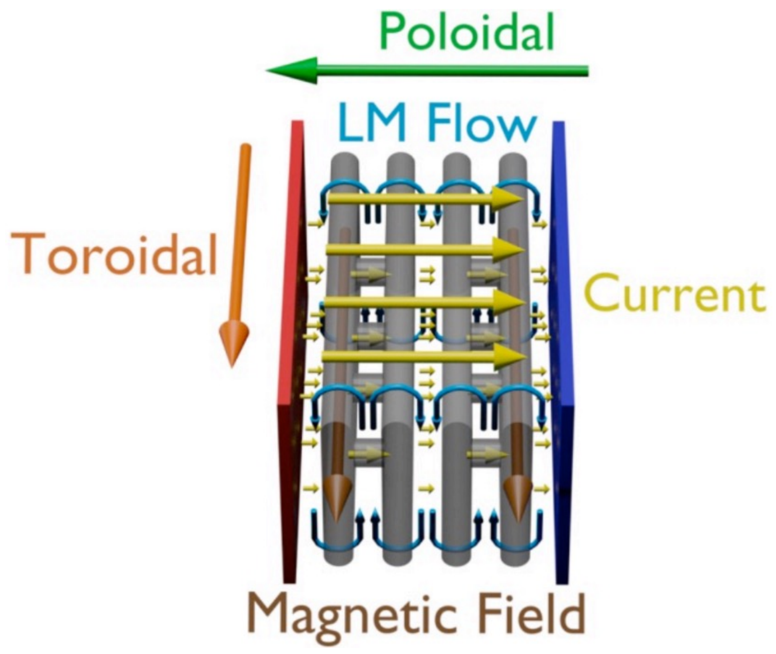

Figure 1. Diagram of electric currents around a slat [2].

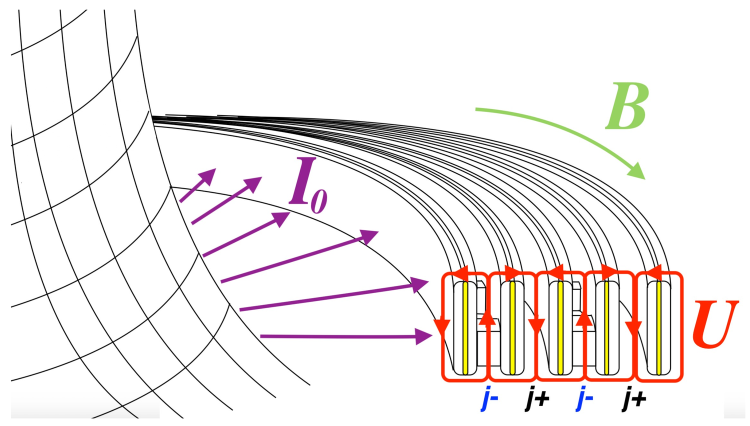

Figure 2. Toroidal divertorlets in a reactor.

Experiments and simulations

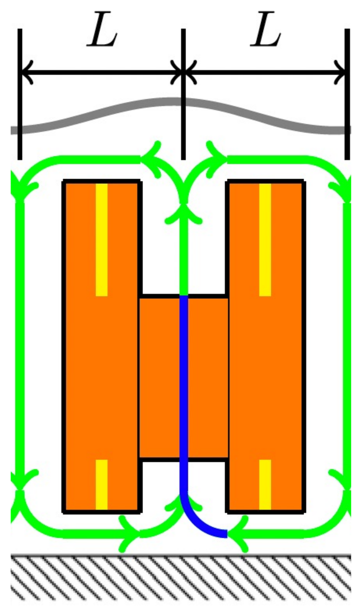

Figure 10. Diagram of a slat [3].

- Tests in LMX-U, PPPL. |**B**|: 0.1 T - 0.33 T.
- Currents: 100 A - 900 A.
- Galinstan (67% Ga, 20.5 In, 12.5% Sn).
- Slats made of copper in a polycarbonate box.
- Plastic tubesused for velocity measurements.
- COMSOL Multiphysics simulations.

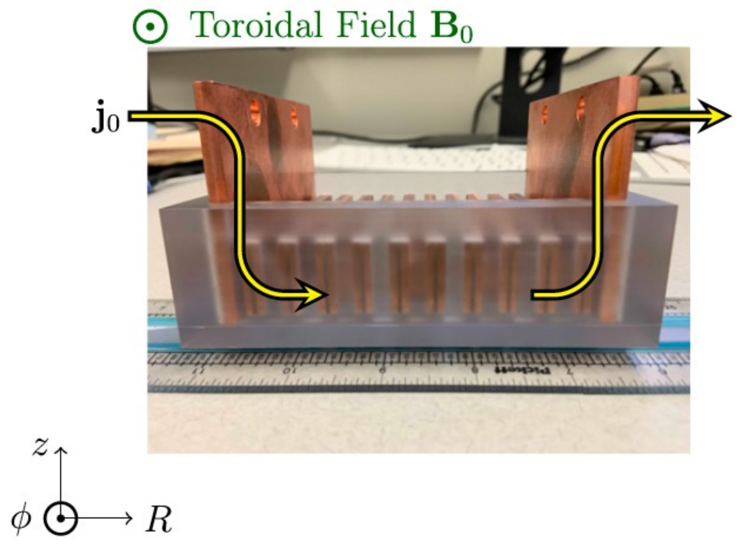

Figure 4. Side-view of divertorlets [3].

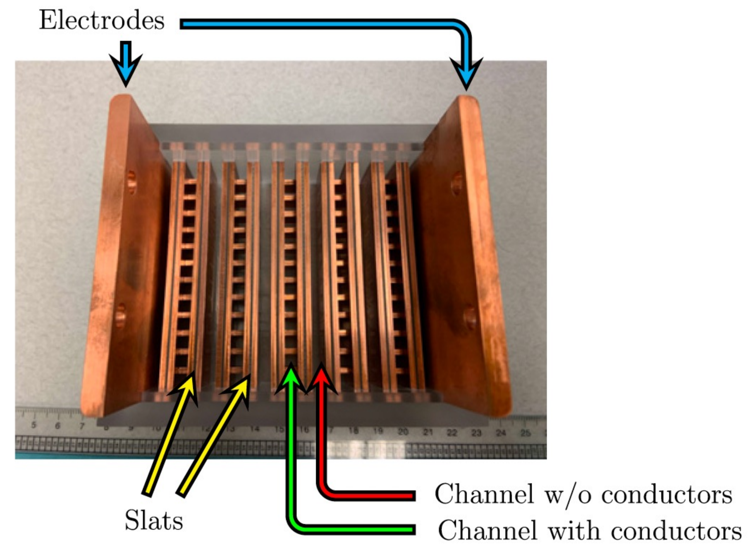

Figure 3. Top-view of divertorlets [3].

Figure 6. Free surface of divertorlets.

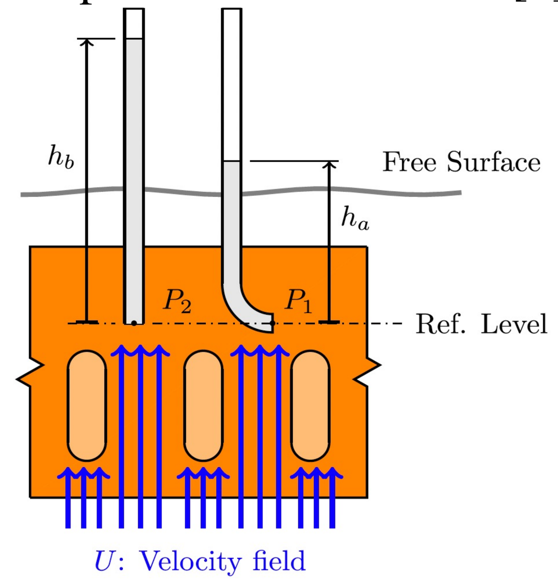

Figure 5. Speed measurements [3].

Results

- Cyclical flow around the slats confirmed (Fig. 6).
- Increasing flow speeds with increasing external current (Fig. 9).
- Balance between $\mathbf{j_0}\times\mathbf{B_0}$ force, MHD drag and viscous drag (Fig. 5).
- Simulations with a uniform heat load of 10 MW/m².

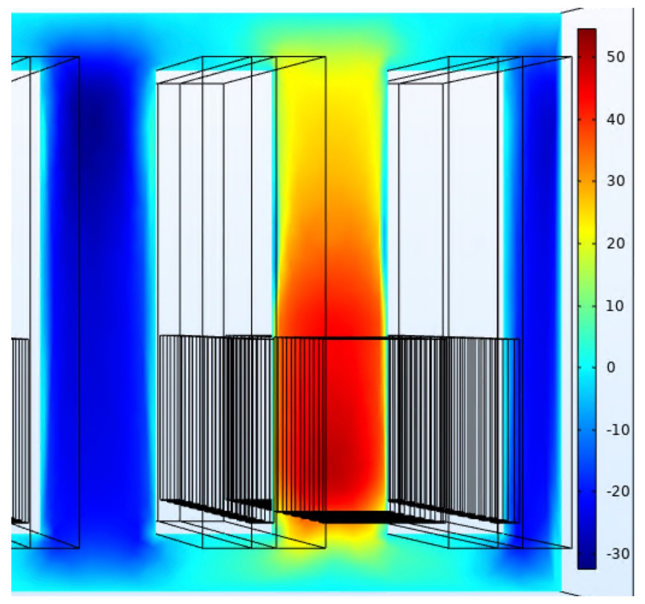

Figure 3. Flow velocity simulation at 0.3 T, 900 A [3].

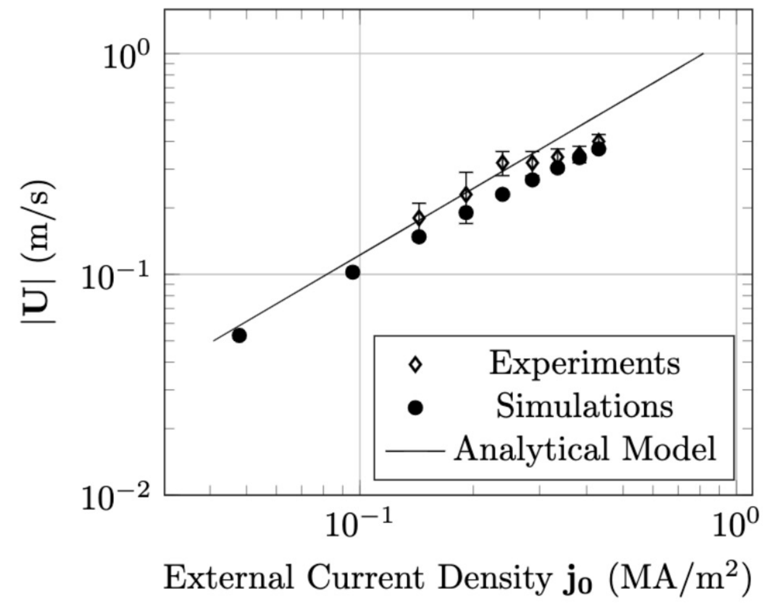

Figure 9. Comparison results [3].

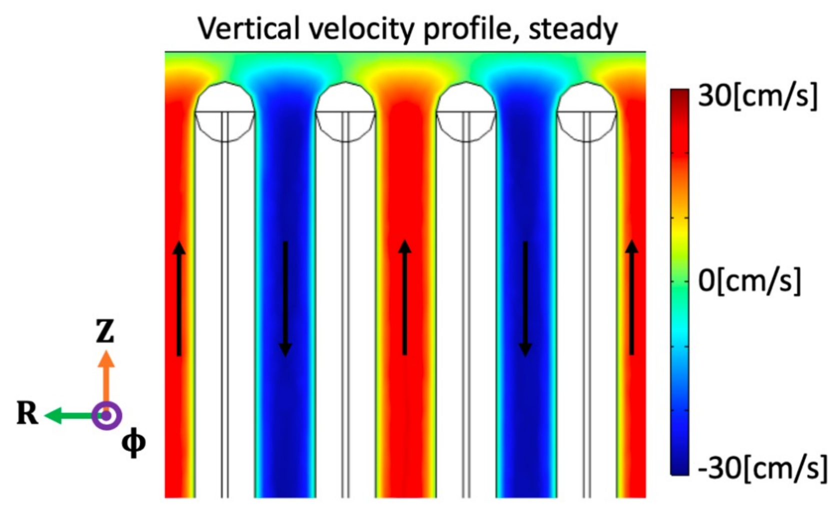

Figure 7. Velocity field from simulations [2]

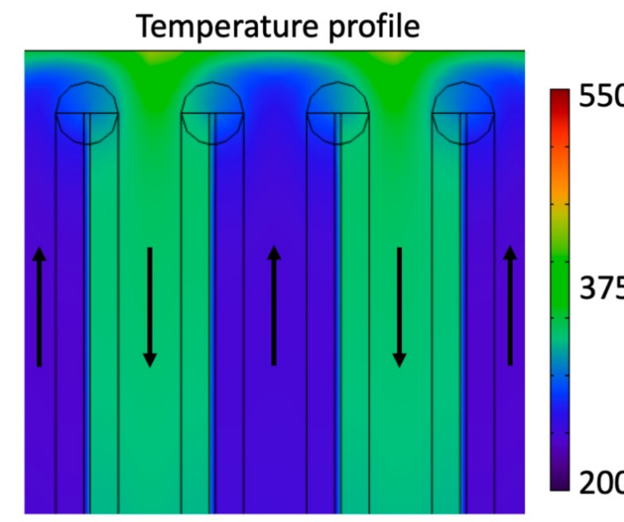

Figure 8. Temperature with 10 MW/m² [2].

Reactor-scale projections

- Simplified heat transfer analysis with a semi-infinite slab of liquid metal.
- **Liquid lithium as the operating LM** and tungsten for the slats/substrate.
- **Operation at 6 T, heat load of 10 MW/m², critical temperature increase of 425 K.**
- Exposure time t of the liquid metal to the plasma: $t = \frac{L}{|\mathbf{U}|}$
- q_{crit} is the maximum permissible heat load for a divertorlets system in a reactor scenario.

$$q_{\text{crit}} = \frac{k\Delta T_{\text{crit}}}{2}\sqrt{\frac{\pi|\mathbf{U}|}{\alpha L}}$$

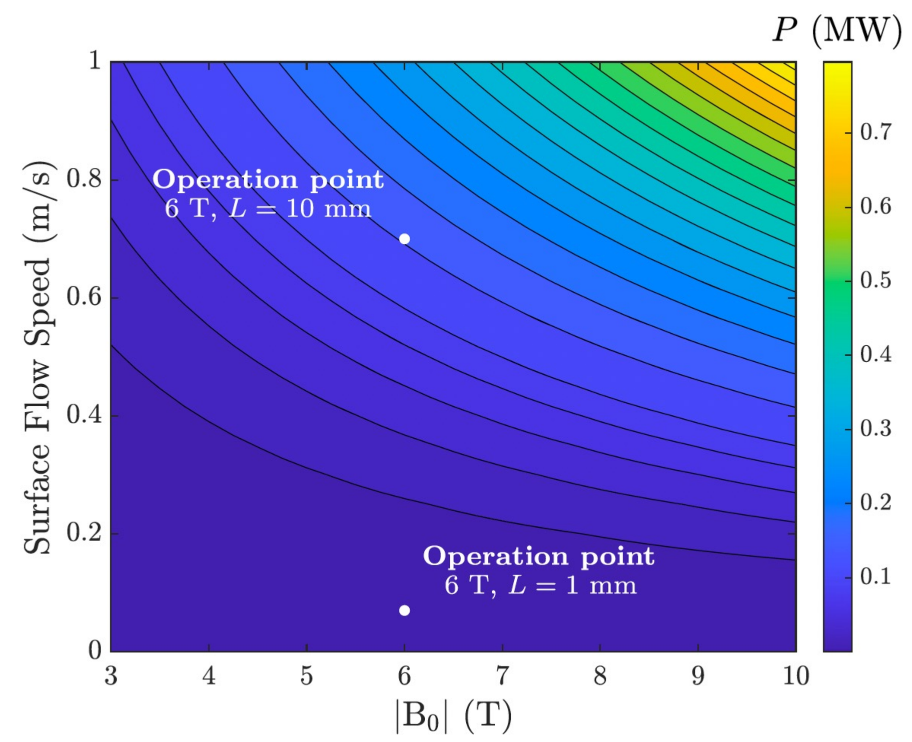

Figure 11. Power requirements at the reactor scale [2].

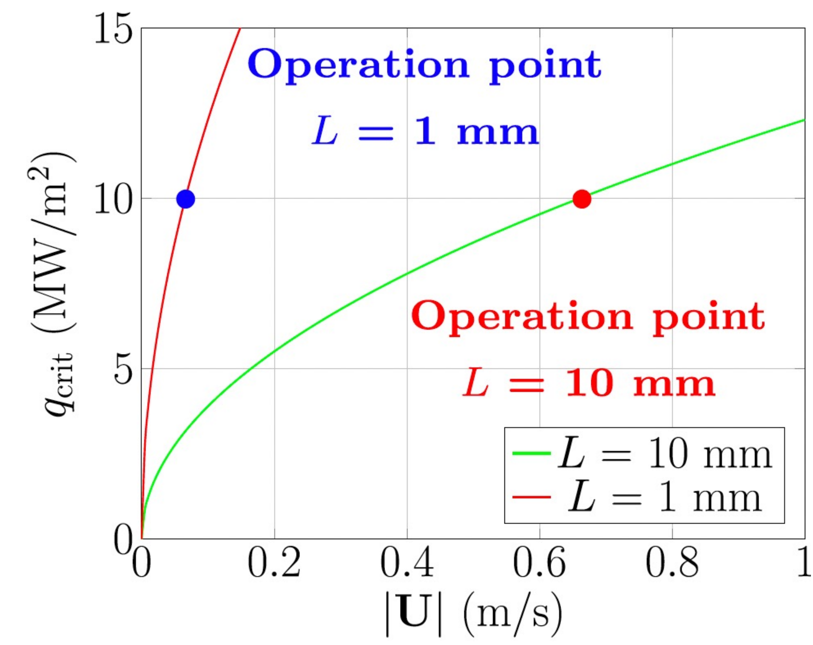

Figure 12. Critical heat flux [2].

Conclusions and future work

- Experiments agreed with simulations and MHD theory at $\mathbf{B} \leq 0.33$ T.
- Projections indicate divertorlets can exhaust heat 10 MW/m².
- Ripples at the free surface must be minimized, L-reduction will help to generate flat free surfaces.
- A cooling system must be integrated to divertorlets for a final design, including TEMHD analysis.

Acknowledgements

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References

[1] E. Kolemen and Adam Fisher, “Divertorlets.”, USA, M-1007. June 3rd, 2020
[2] A. Fisher, et al, “Liquid metal “divertorlets" concept for fusion reactors”, Nuclear Materials and Energy, vol. 25, p. 100855, 2020.
[3] Saenz, F et al, E. Divertorlets concept for low-recycling fusion reactor divertor: experimental, analytical and numerical verification. United States: N. p., 2022. Web. doi:10.1088/1741-4326/ac6682.