Lorentz force propulsion on free-surface liquid metal channel flow

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Motivation

Fast-flowing liquid metal divertors could solve problems imposed on solid components (melting and erosion). However, they suffer severe MHD drag, causing excessive liquid-metal evaporation and possible plasma disruptions.
The injection of an electric current through the liquid metal combined with a transverse magnetic field B, can generate an accelerating force j × B in the flow direction.

$$t_{cr} = (\Delta T/2q)^2 \pi k \rho c_p$$
$$\rightarrow\ t_{cr} \approx 0.03 \pm 0.02[s]$$
$$\rightarrow\ u_{cr} \approx 11.5 \pm 4[m/s]$$

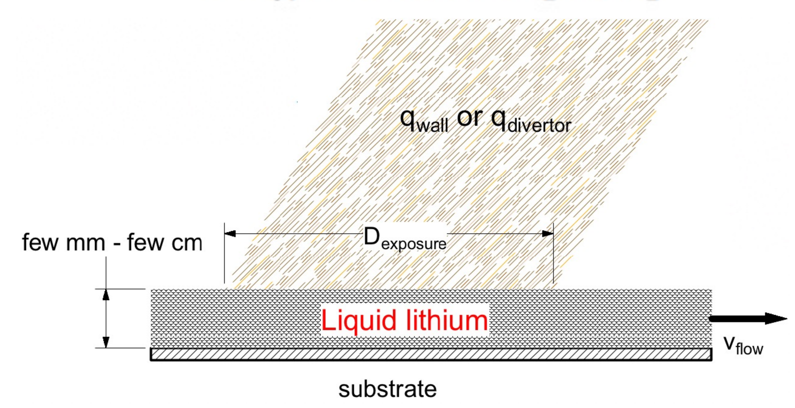

Fig 1. Liquid metal slab [1].

Issues with operation at the reactor scale

- Currents to overcome MHD drag from $\mathbf{B_n}$ may require ~10% of power output of DEMO.
- Overcoming drag from toroidal fields→larger power requirements.
- Fringing effects of injected currents cause flow detachment from electrodes: unstable flow.

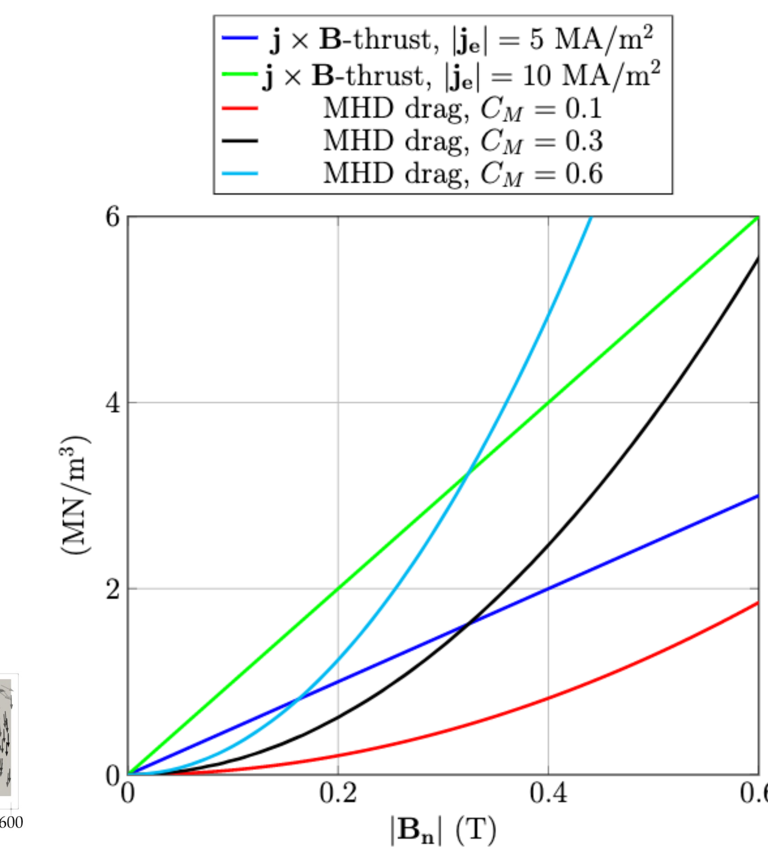

Fig. 5. Power requirements

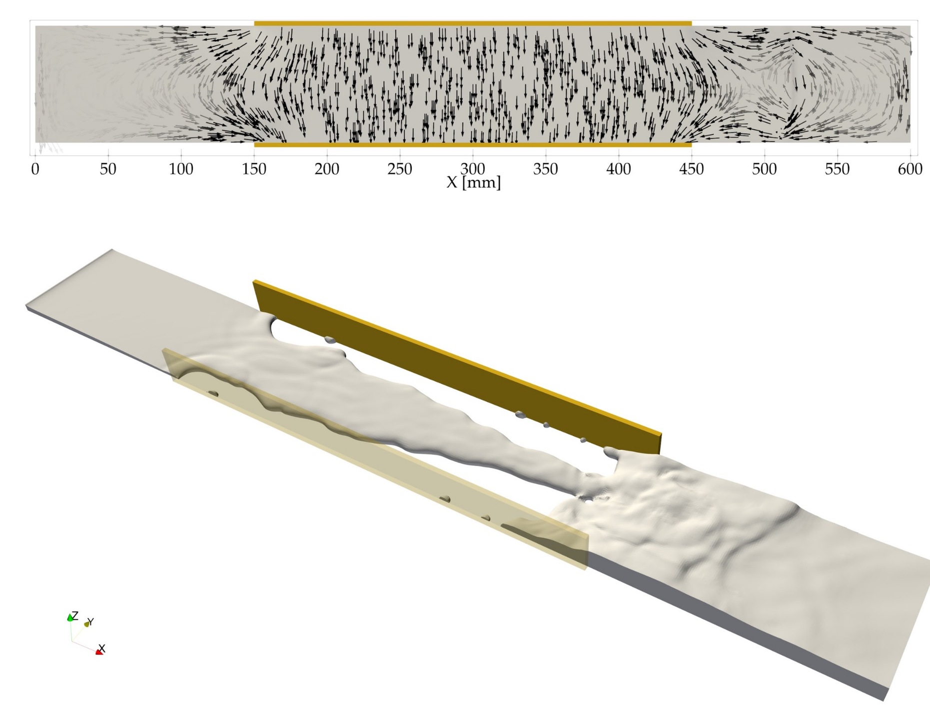

Fig. 6. Fringing effects

- Metallic substrates carry most of injected current.
- Flow acceleration is achieved with insulated bottom wall for substrate (Figs. 8-9).
- Developing flows induce axial currents which push the flow to one side of the channel:
  - Non-uniform injected current density causes unstable acceleration.
  - Issues with overheating from plasmas.

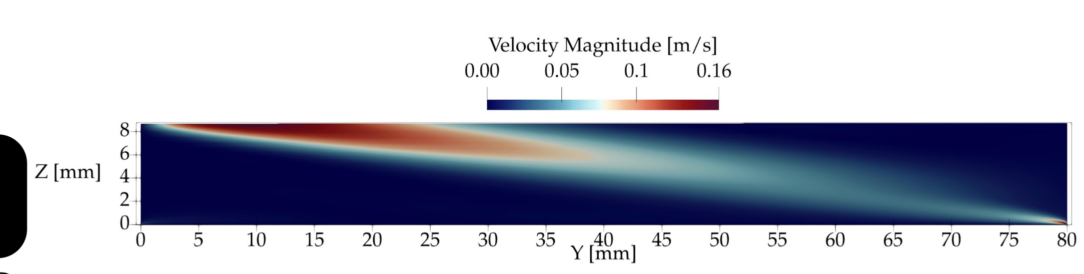

Fig. 7. Cross section velocity field with tungsten substrate ($\mathbf{B_n}$ = 0.1 T, $\mathbf{B_\phi}$ = 1 T).

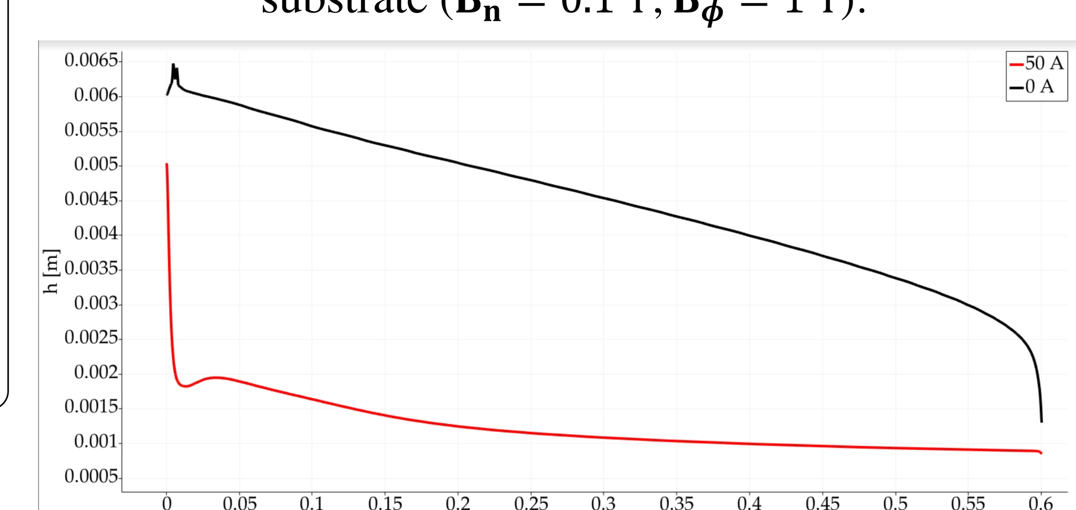

Fig. 8. Height for insulated substrate ($\mathbf{B_n}$ = 0.1 T, $\mathbf{B_\phi}$ = 1 T)

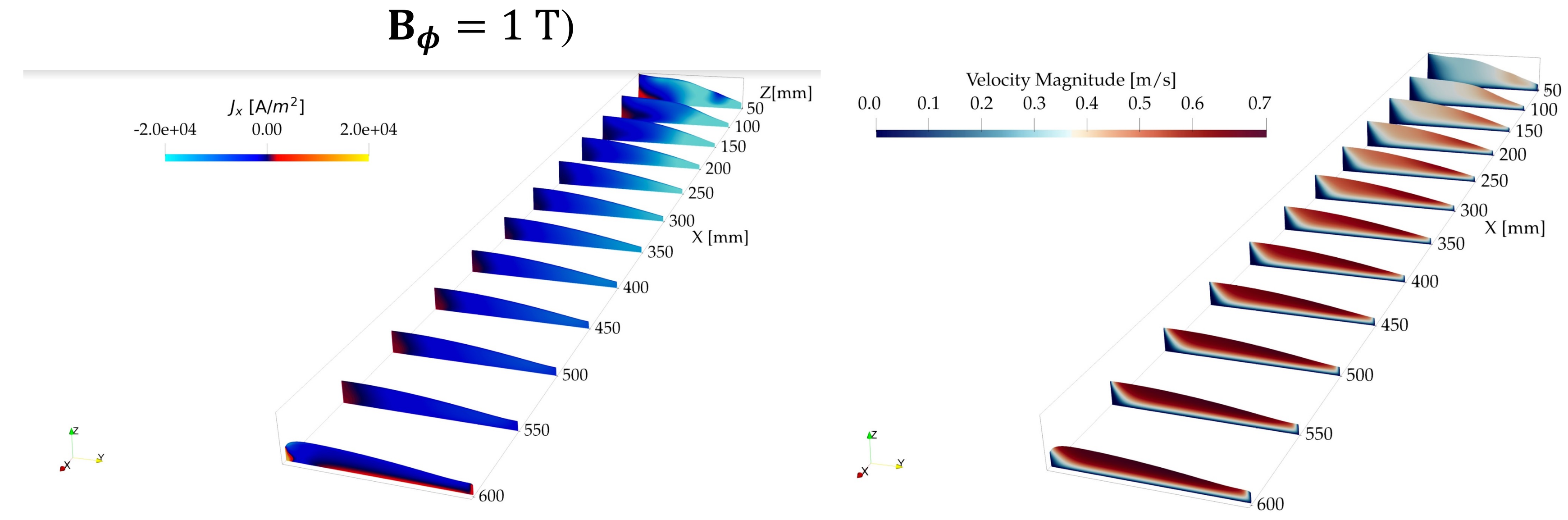

Fig. 9. Flow velocity and axial currents for insulated substrate ($\mathbf{B_n}$ = 0.1 T, $\mathbf{B_\phi}$ = 1 T, 50 A)

Acceleration through jxB thrust

An arrangement of separate chutes (divertor cassettes) with electrodes to apply external currents on liquid metal flows. In combination with magnetic fields, Lorentz-force propulsion is achieved.

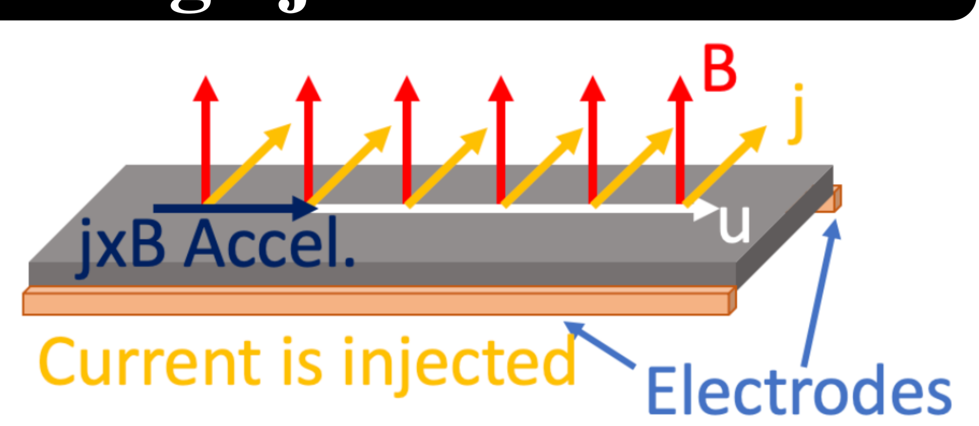

Figure 2. Electrodes for current injection.

Experiments

- LMFREX channel from Kyoto University.
- Tests at the National Institute for Fusion Science (NIFS).
  - $\mathbf{B_n}$ normal fields(up to 1.2 T).
  - Electric currents (up to 120 A).
- Galinstan as liquid metal (67% Ga, 20.5% In and 12.5% Sn).
- Laser sheet for local height measurements of liquid metal flow→local average speed.

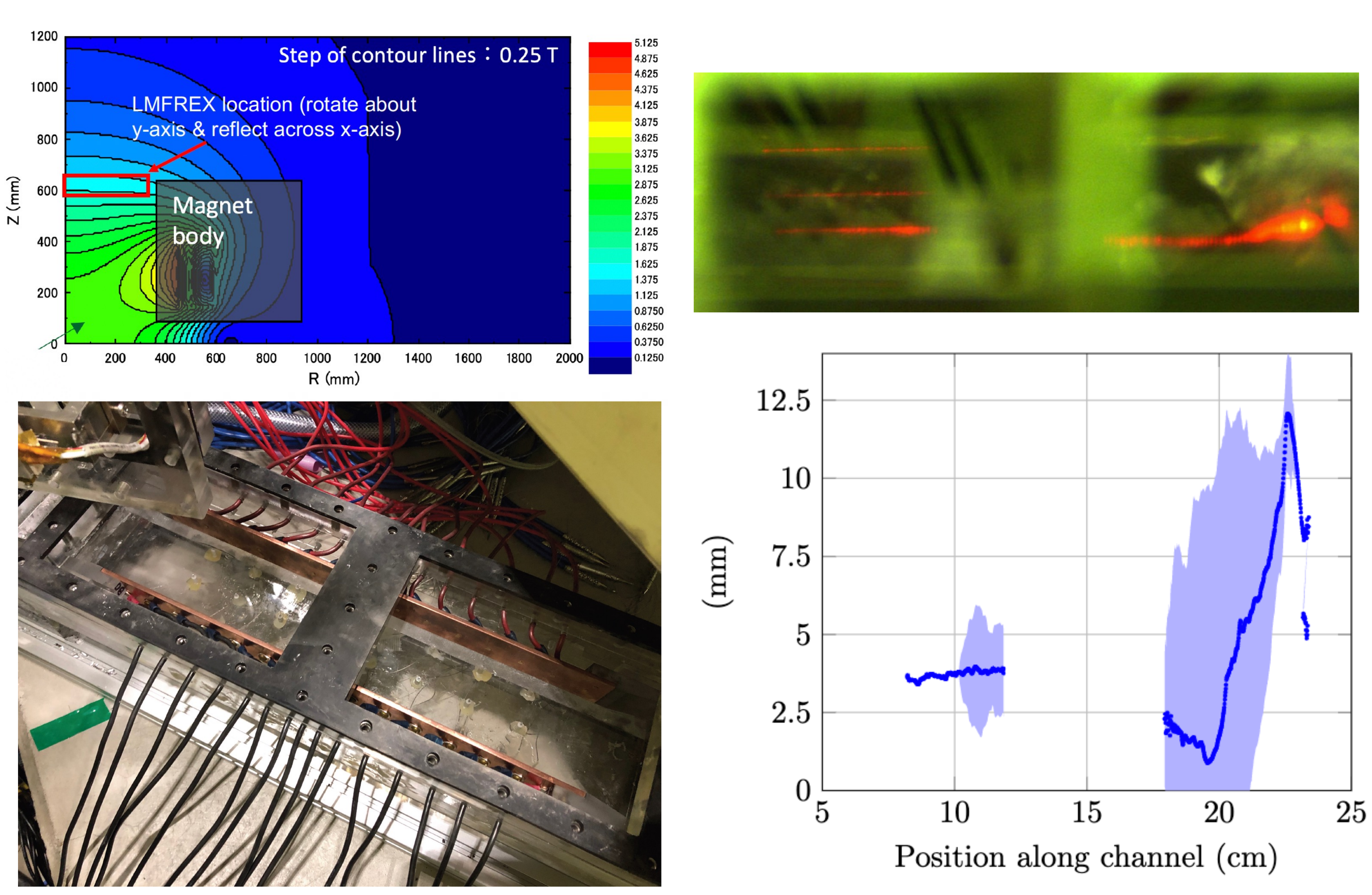

Fig. 3. Experimental setup

Analysis

- 2D Flow, steady state Navier Stokes Equations.
- OpenFOAM simulations.
- Agreement in flow depth and forces.
- Hydraulic jump was observed

$$\nabla \cdot \mathbf{U} = 0$$
$$\mathbf{U} = (u, 0, w)$$
$$\rho(\mathbf{U}\cdot\nabla)u = -\frac{\partial p}{\partial x} + (\mathbf{j}\times\mathbf{B})\cdot\mathbf{i} + \mu\frac{\partial^2}{\partial z^2}u$$

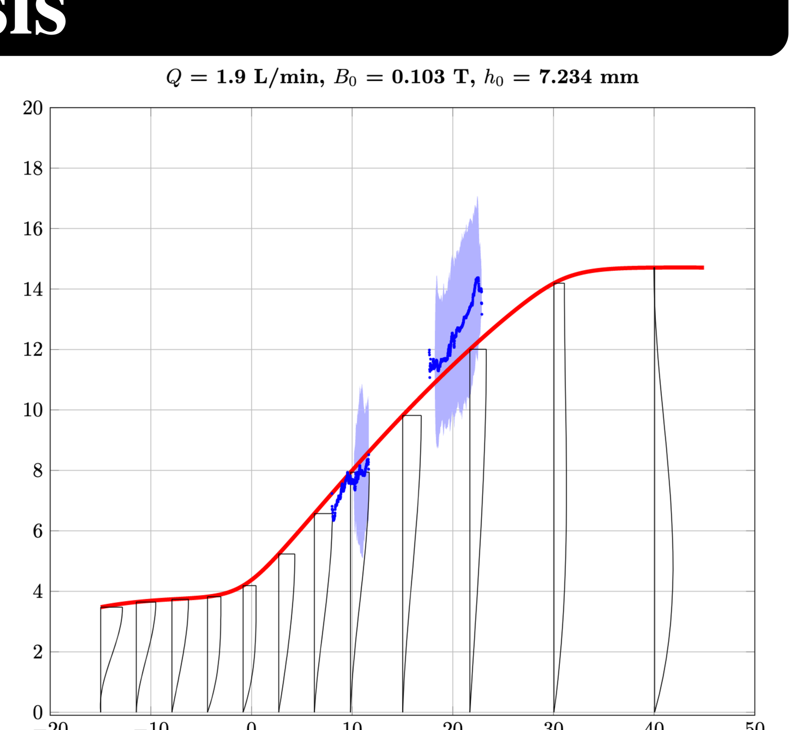

Fig. 4. Analytical review

Conclusions

- Requirements to overcome MHD drag are incompatible with cost-effective reactors.
- Simplified analytical equations to describes MHD flows do not encompass relevant 3D effects. Simulations are required.
- Current injection may accelerate a liquid metal flow but also causes unstable behavior.
- Axial currents in developing linear flows are inevitable and pose issues for reactor operation.

Acknowledgements

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References

[1] E. Kolemen, M. Hvasta, R. Majeski, R. Maingi, A. Brooks, and T. Kozub, “Design of the Flowing LIquid Torus (FLIT),” Nuclear Materials and Energy, vol. 19, pp. 524–530, May 2019, doi: 10.1016/j.nme.2019.01.005.