3D-MHD Liquid-metal-flow simulations and experiments in Oroshhi-2/NIFS and LMX-U/PPPL for divertor applications

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Overview

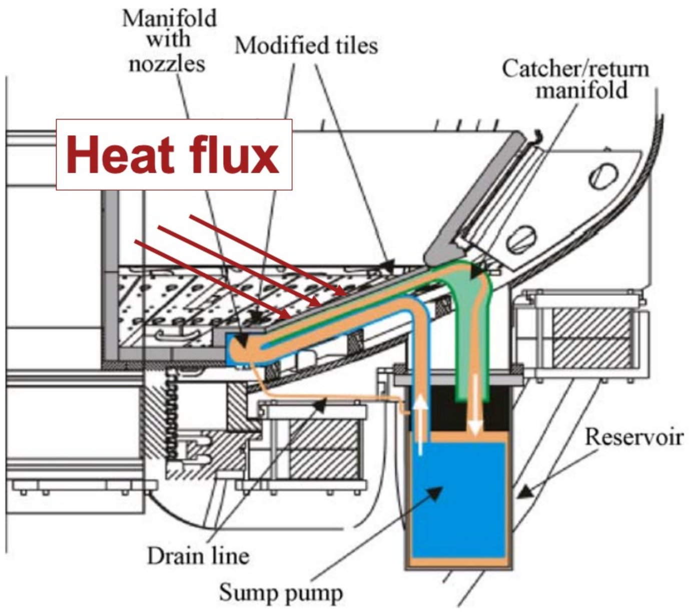
- **Motivation**
- **LMX-U**
  - Operational parameters
- **Liquid metal flows in open channel**:
  - Experiment and simulations.
  - Operational advantages and issues.
  - **Objective: to test the feasibility of high-speed-liquid-metal-flow divertor.**
- **Divertorlets**:
  - Experiment and simulations
  - Projections.

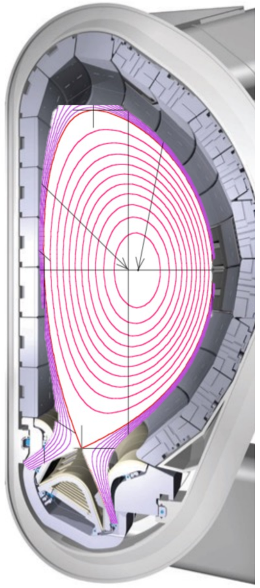
Motivation

- Liquid metal flows for heat exhaust in divertors of fusion reactors.

- Non-evaporative liquid metal divertor is needed.
  - Fast flow ~ 1 m/s - 20 m/s for a standard divertor (length ~ 10 cm).

- Reactor scenario:
  - Severe MHD drag.
  - Free-surface stability of fast flows.

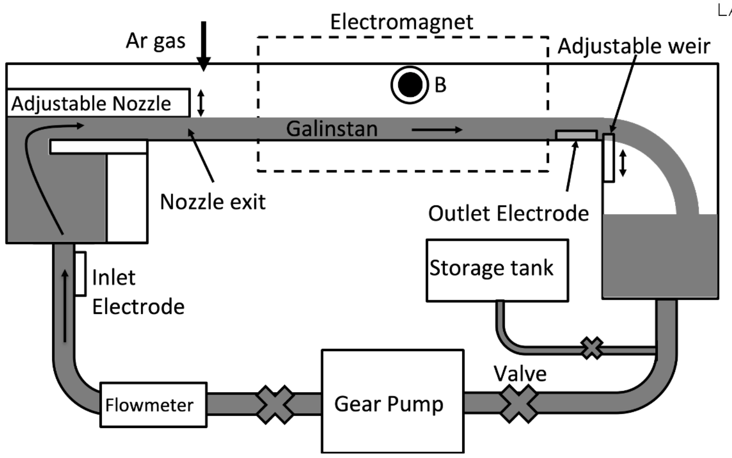


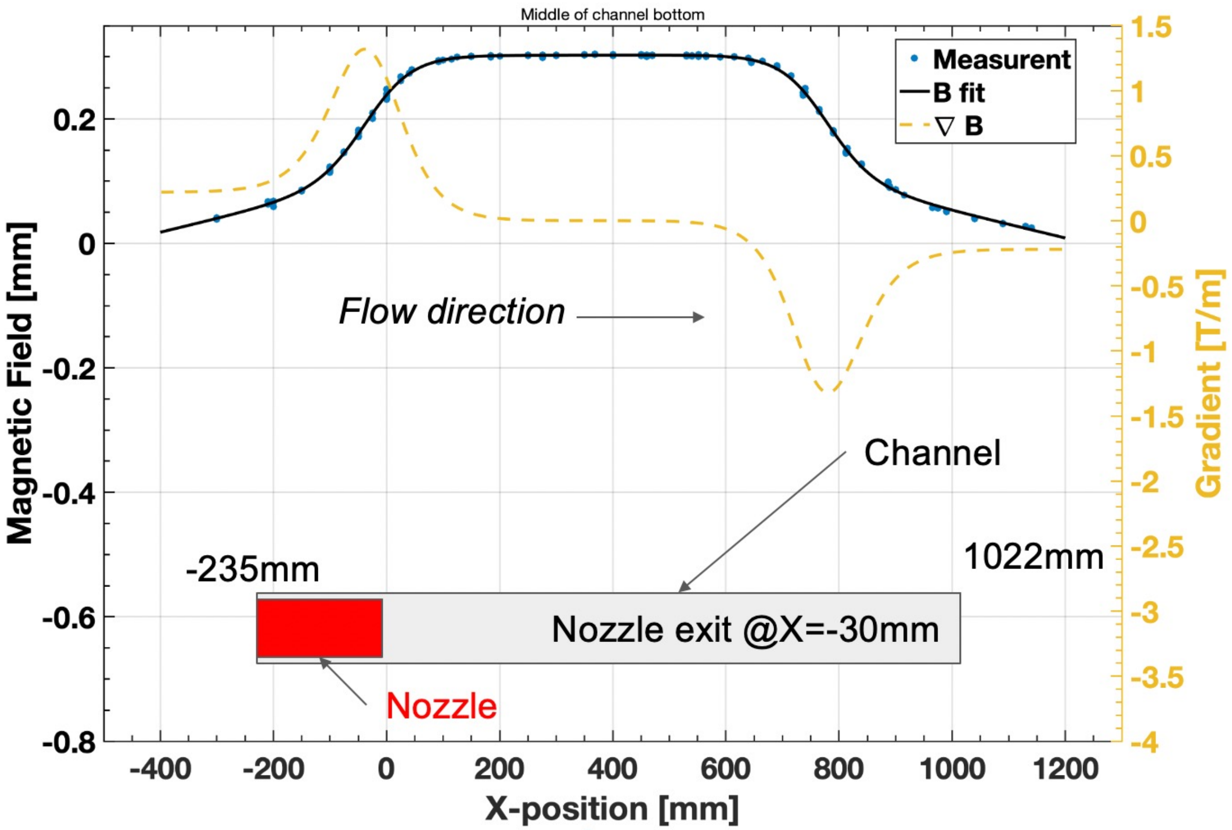


Ying [FED, 2004]

Liquid Metal R&D without plasmas

- **Aim**: To understand liquid metal flows at small scale.
- **New Divertor Ideas:** $j \times B$-forces to control of the LM flow and pumping.
- **Liquid Metal eXperiment Upgrade** (LMX-U) operating at PPPL.
  - Galinstan (GaInSn alloy).
    - Electrical conductivity: 3.1 MS/m, (Li: 3.43 MS/m).
- Max. B: 0.33 T

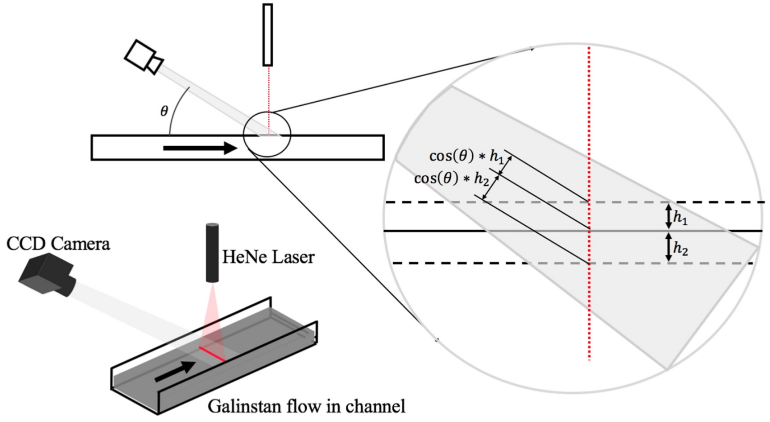




Liquid Metal R&D without plasmas

- **Liquid Metal eXperiment Upgrade** (LMX-U)
  - Height-adjustable nozzle at inlet allows inlet depth to be changed:
    - Max. flow speed: 2 m/s
    - Removable nozzle
  - Inclination angle range: 0˚ - 7˚.
  - Movable channel.

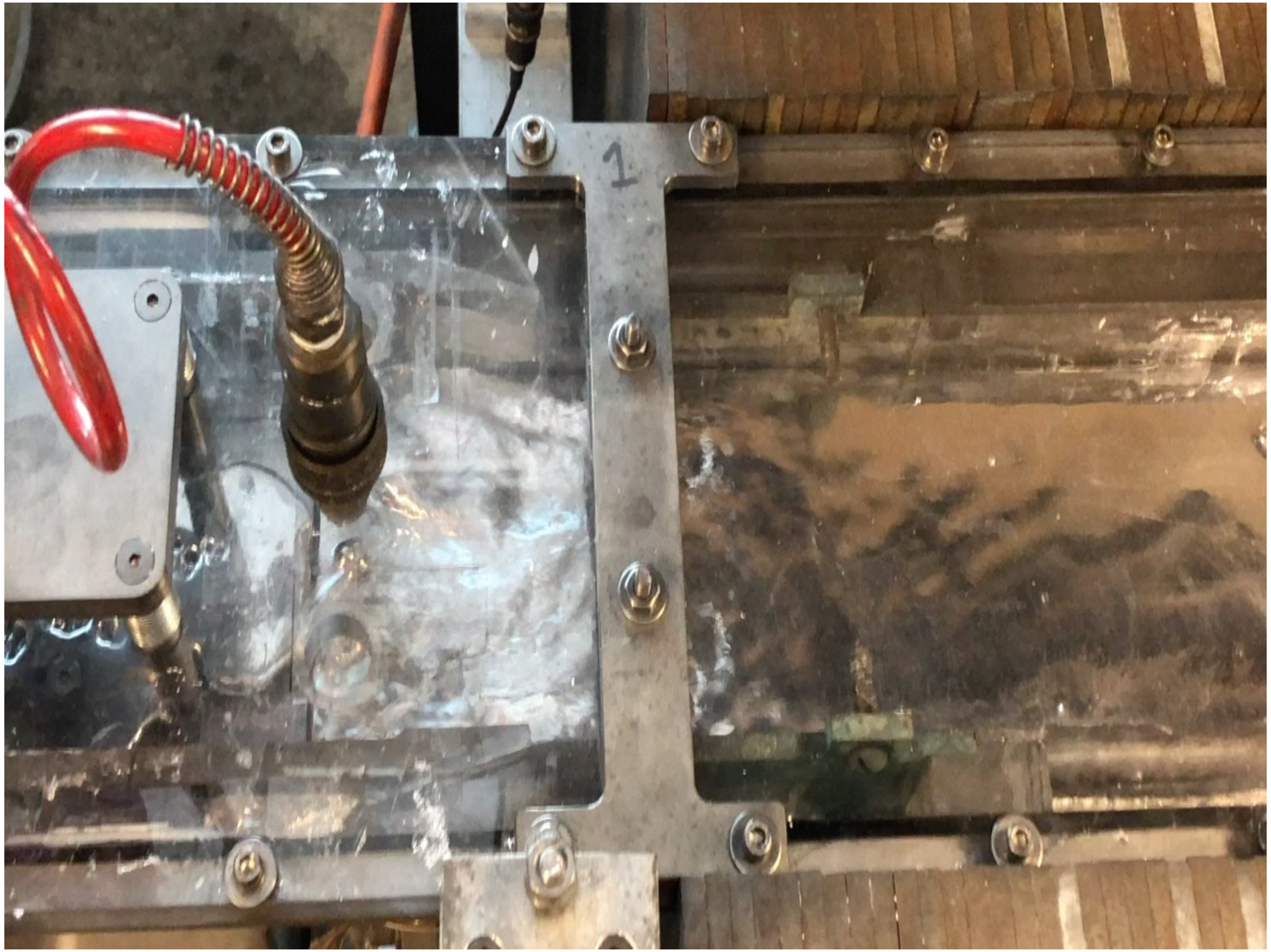
- **Diagnostics**
  - Laser sheet for depth measurements.



Hvasta [NF, 2018]

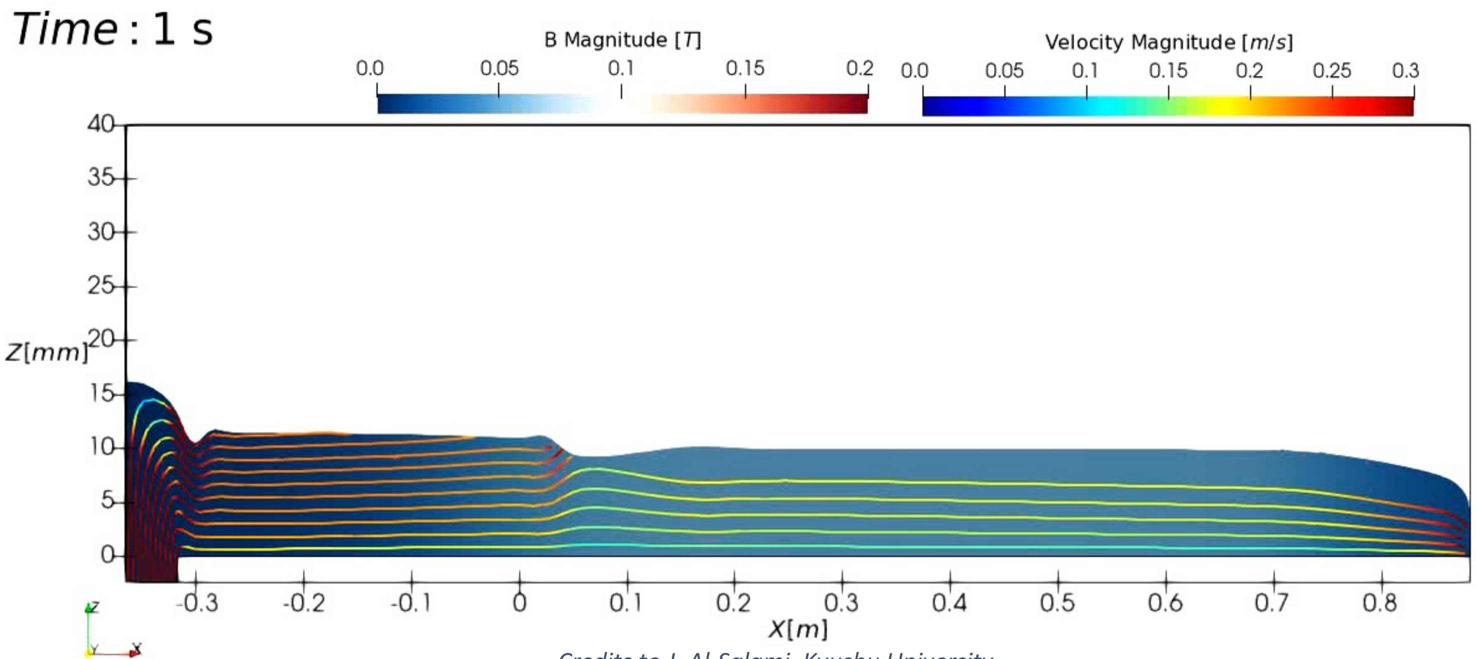
<u>LMX-U publications by Kolemen group:</u>
1. Kusumi, FEDC 111 1193 (2016)
2. Kusumi, FEDC 72,4, 796 (2017)
3. Kusumi, FEDC 01, 067 (2018)
4. Hvasta, RSI 88 013501 (2017)
5. Hvasta, Nucl. Fusion, (2017)
6. Hvasta, MST (2017)
7. Hvasta, MST (2018)
8. Hvasta. FST (2020)
9. Modestov, Nucl. Fusion, (2017)
10. Fisher, Phys. Fluids (2018)
11. Fisher, NME, 19, 101-106 (2019)
12. Fisher, NME, (2020)
13. Kolemen, NME (2019)
14. Saenz, Nucl. Fusion, (2022)

Liquid Metal Flows in Open Channel

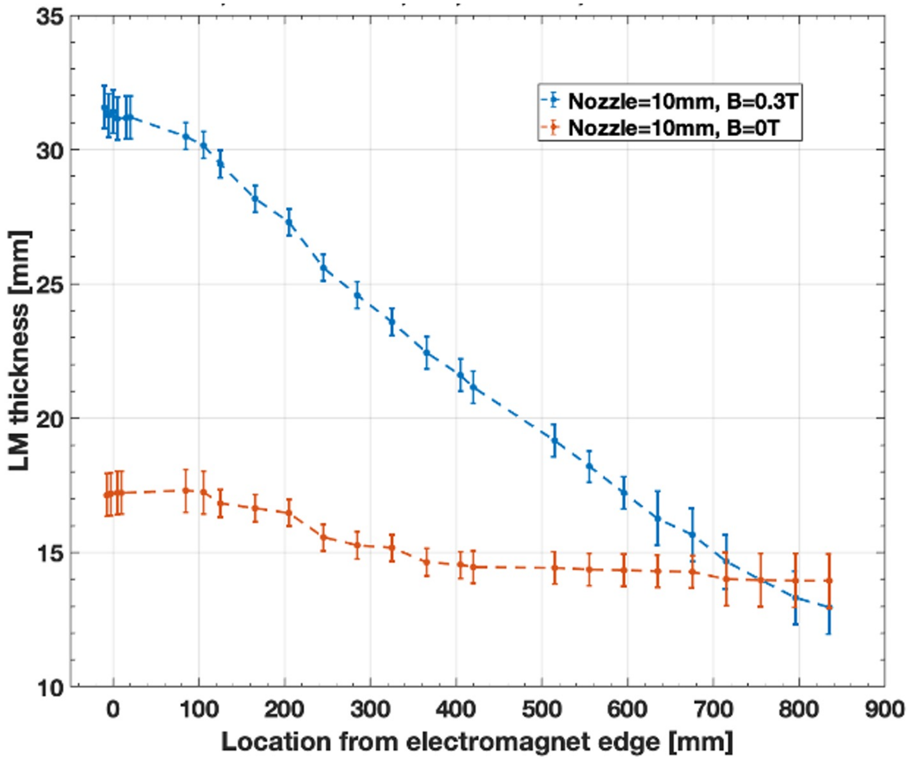


MHD drag on liquid metal flows

- $\mathrm{F_{MHD}} = \sigma\,(\mathrm{E} + \mathrm{U}\times\mathrm{B})\times\mathrm{B}$
  $\sim C_M \sigma |\mathbf{U}||\mathbf{B}|^2$
- Substrate conductivity:
  - Cu: 58.7 MS/m, 2.36 mm wall thickness: Ha ~ 590, Re ~ 4270

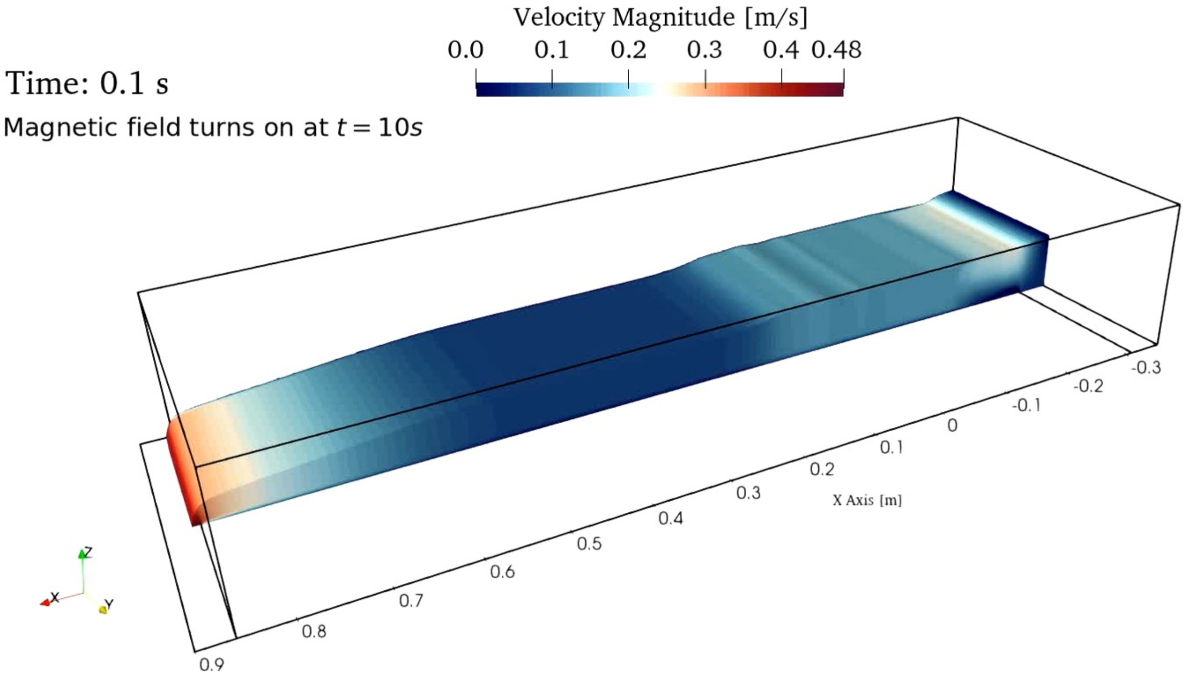


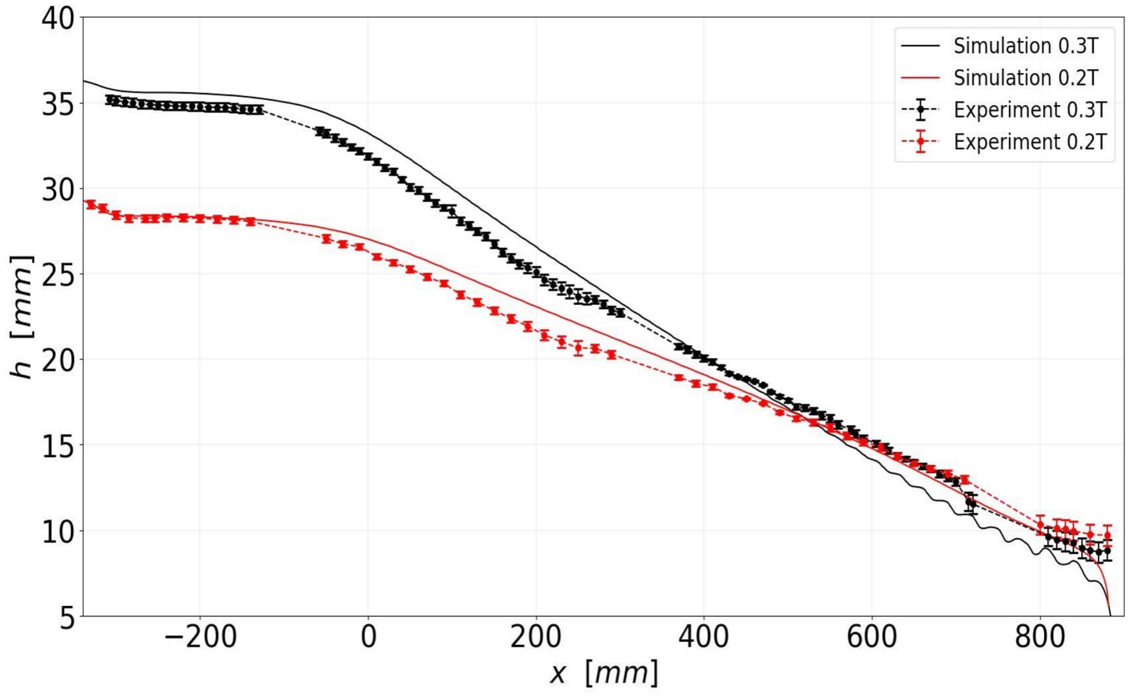
Credits to J. Al-Salami, Kyushu University



3D MHD Free Surface Flow Simulation Code

- MHD Solver with OpenFOAM



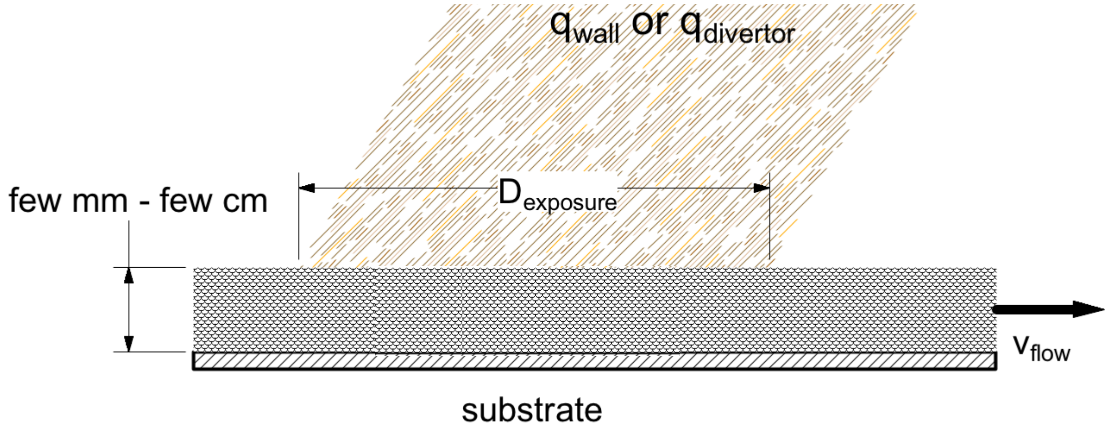


- $t_w = 2.36$ mm
- Cu wall
- $Q = 16.3$ L/min

Credits to J. Al-Salami, Kyushu University

Issues at the reactor scale

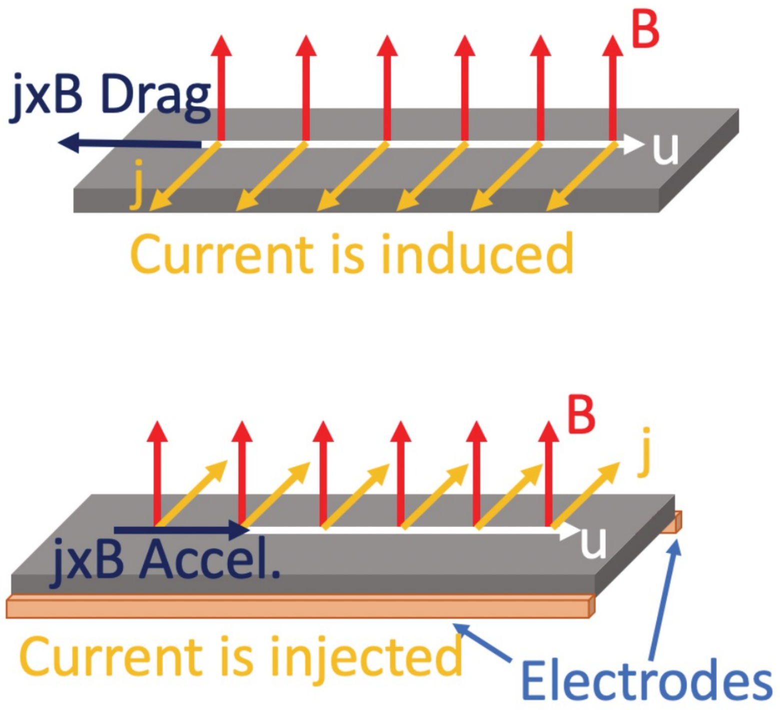
- Non-evaporative liquid metal divertor is needed.
  - Fast flow ~ 1 m/s - 20 m/s for a standard divertor (length ~ 10 cm).

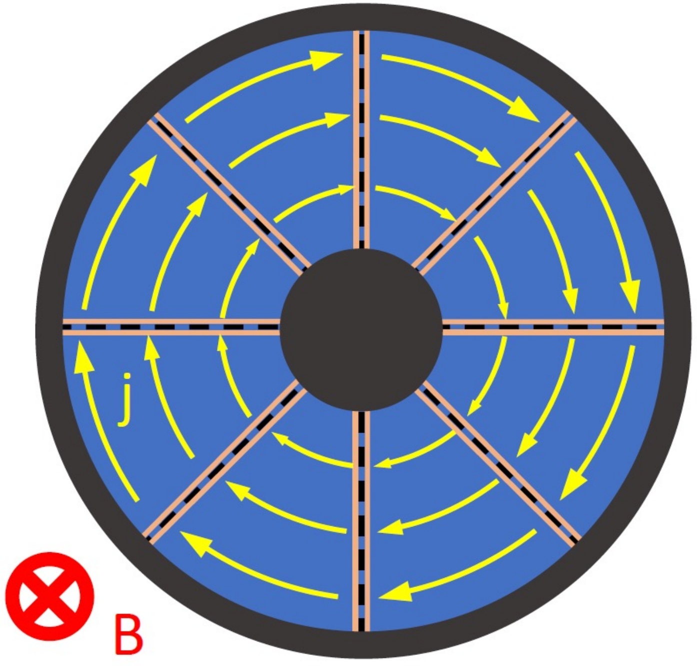


Kolemen [NME, 2019]

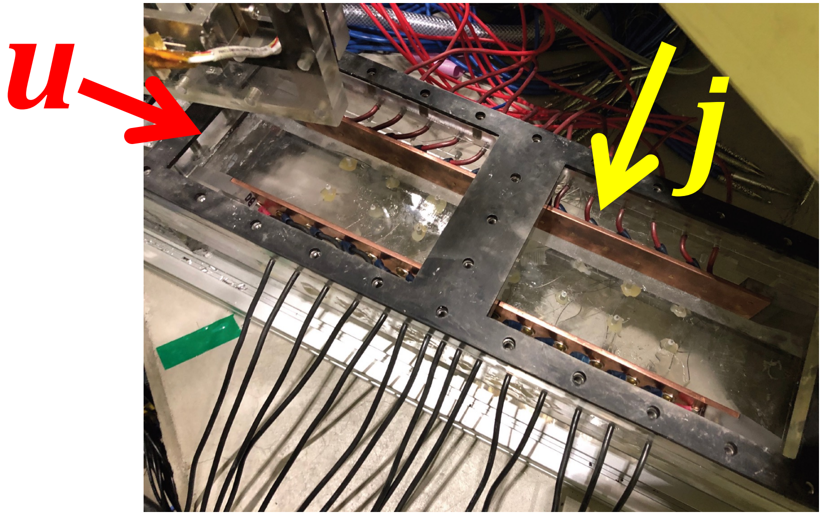
j×B propulsion

- Countering MHD drag with external currents



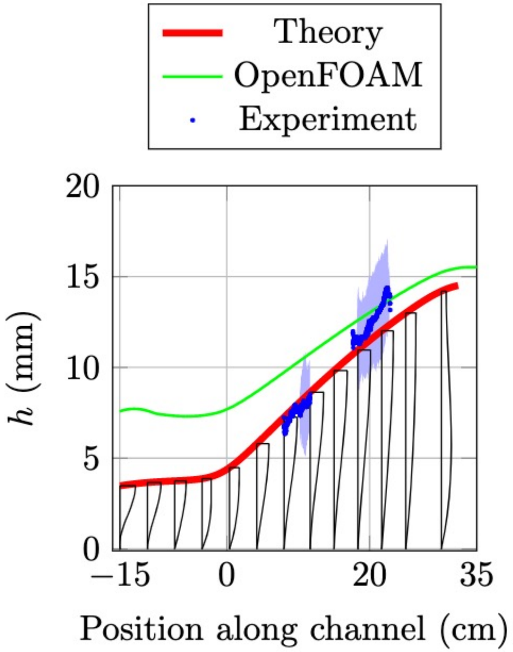


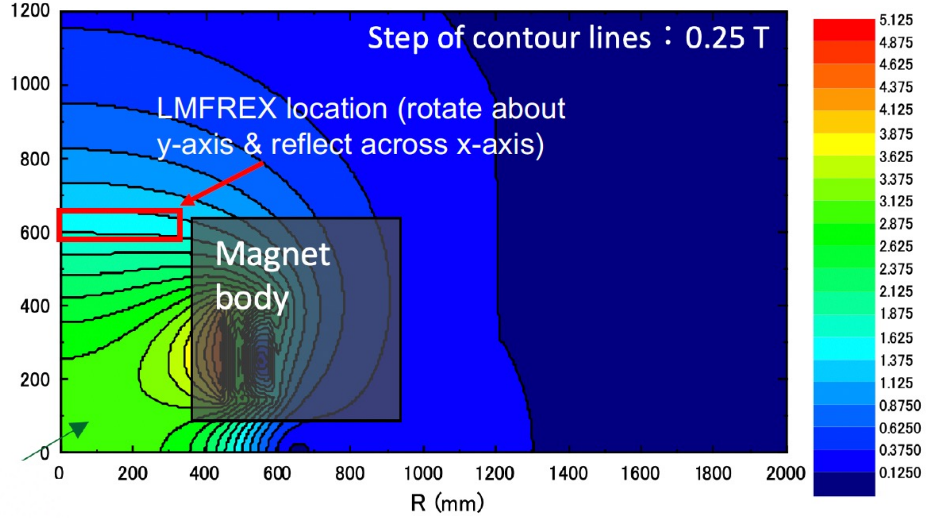
NIFS Oroshhi-2/Kyoto University Collaboration



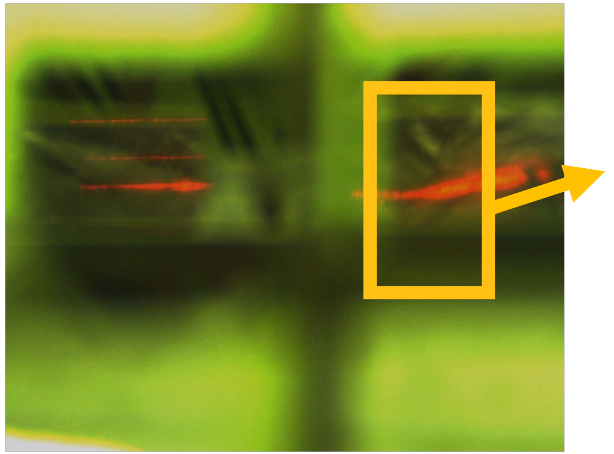
$\otimes$ **B**

60 A, 0.1 T →



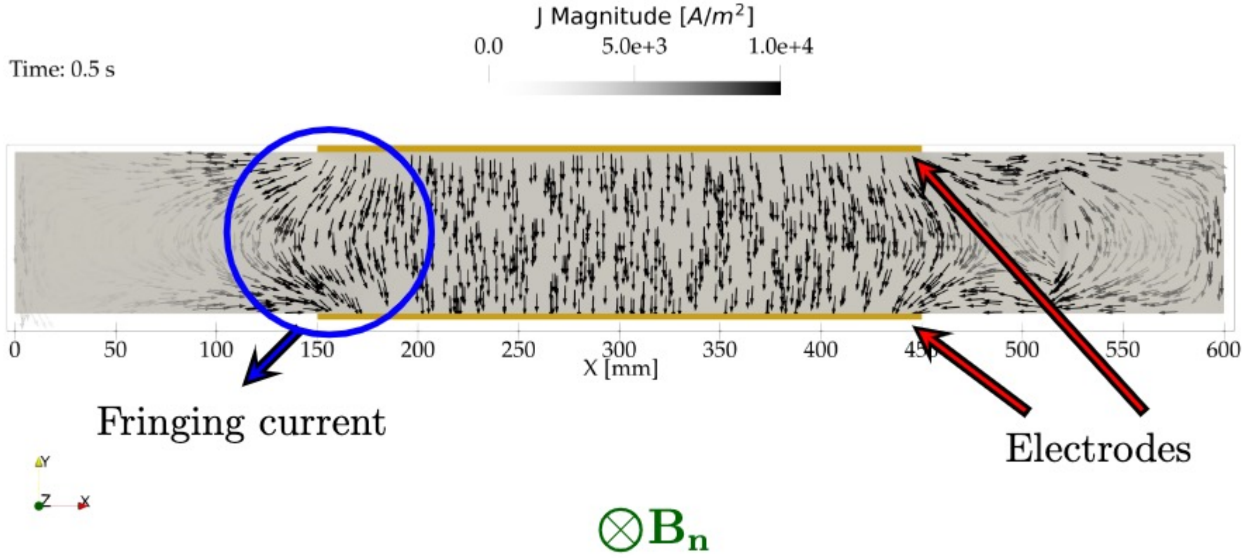


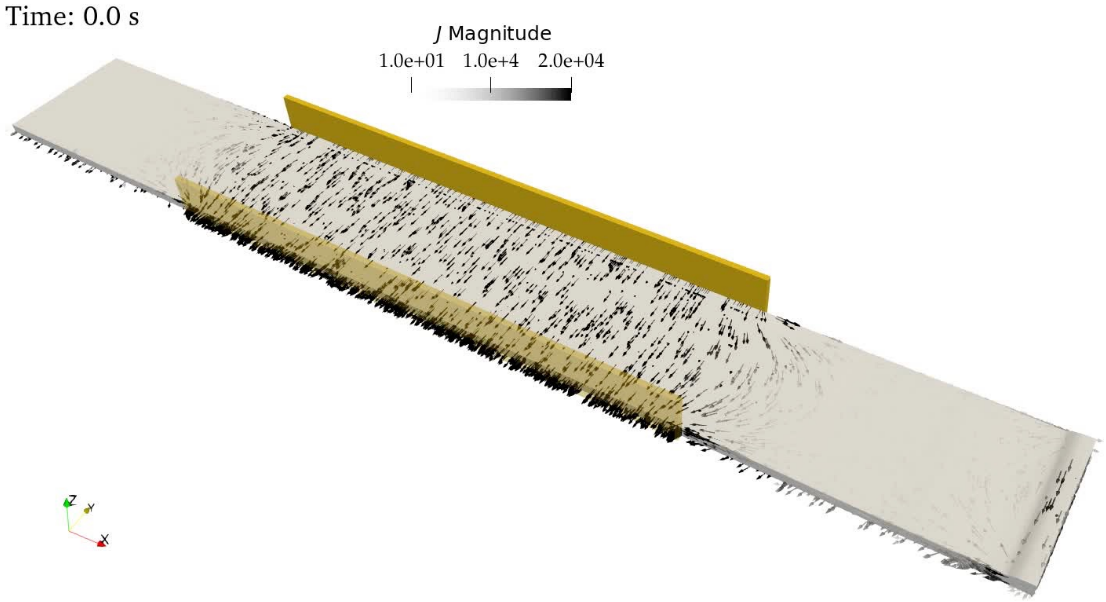
120 A, 0.1 T



Jump-like discontinuity!

Fringing currents

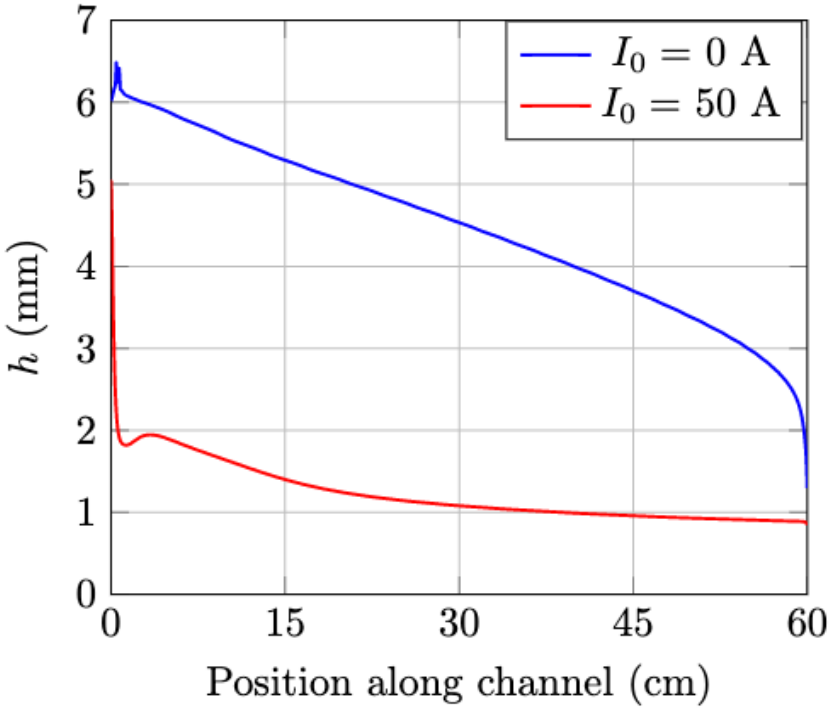




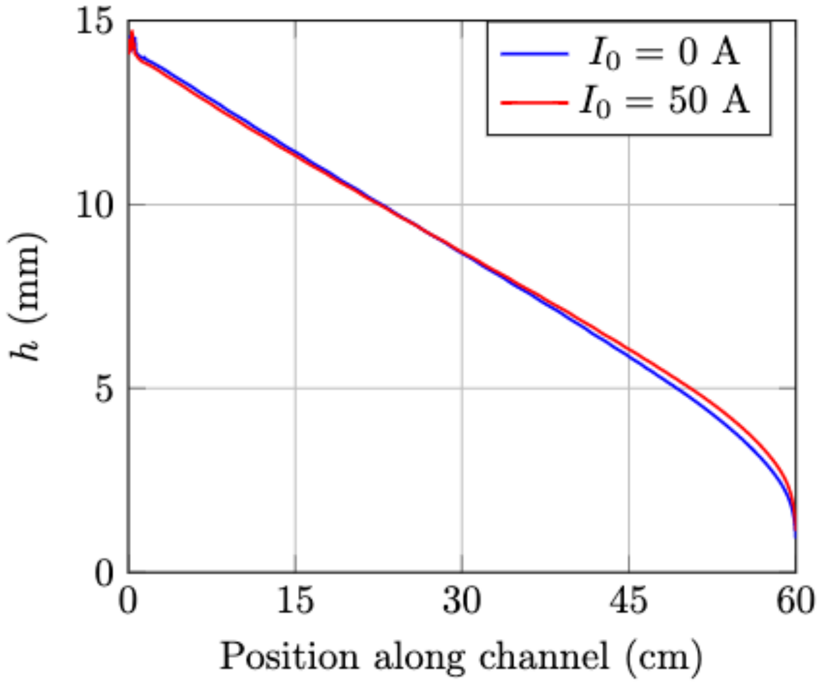
Operation at higher magnetic fields

- $\mathbf{B_n} = 1$ T, liquid lithium
- Effects of substrate conductivity

Insulated bottom substrate

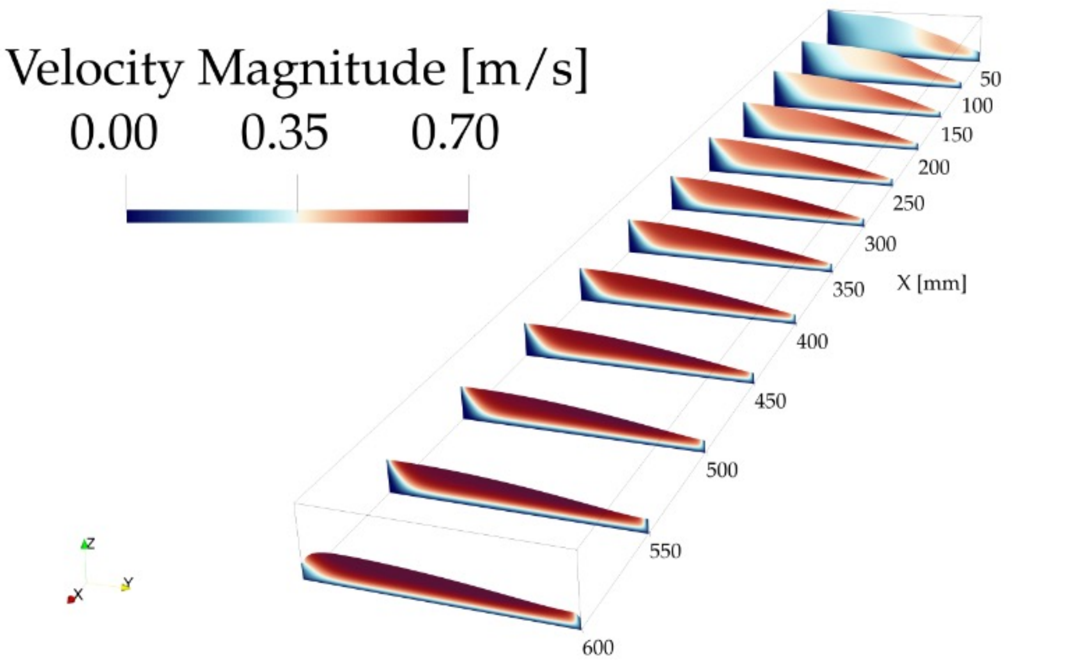


Tungsten bottom substrate

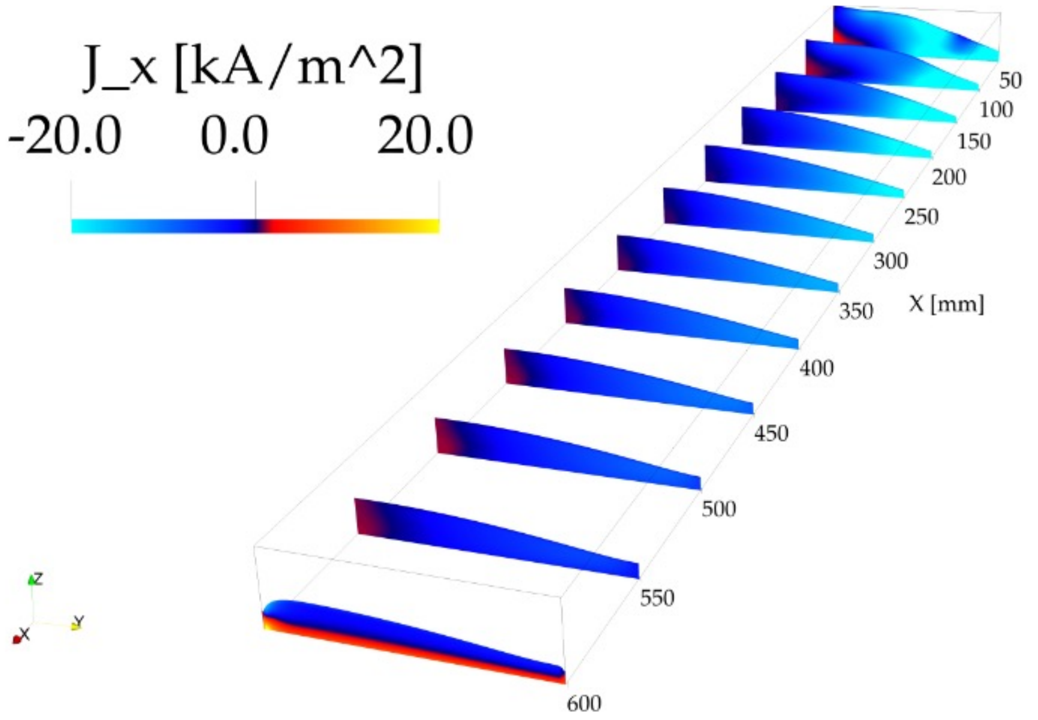


Developing flows

- Axial currents due to stream-wise gradients of velocity
  - Push flow to one side due to $\mathrm{B_n}$
  - Eject liquid-metal drops into the plasma due to $\mathrm{B_T}$



(c) Velocity profiles for $I_0 = 50$ A. h is increased by a factor of 10.

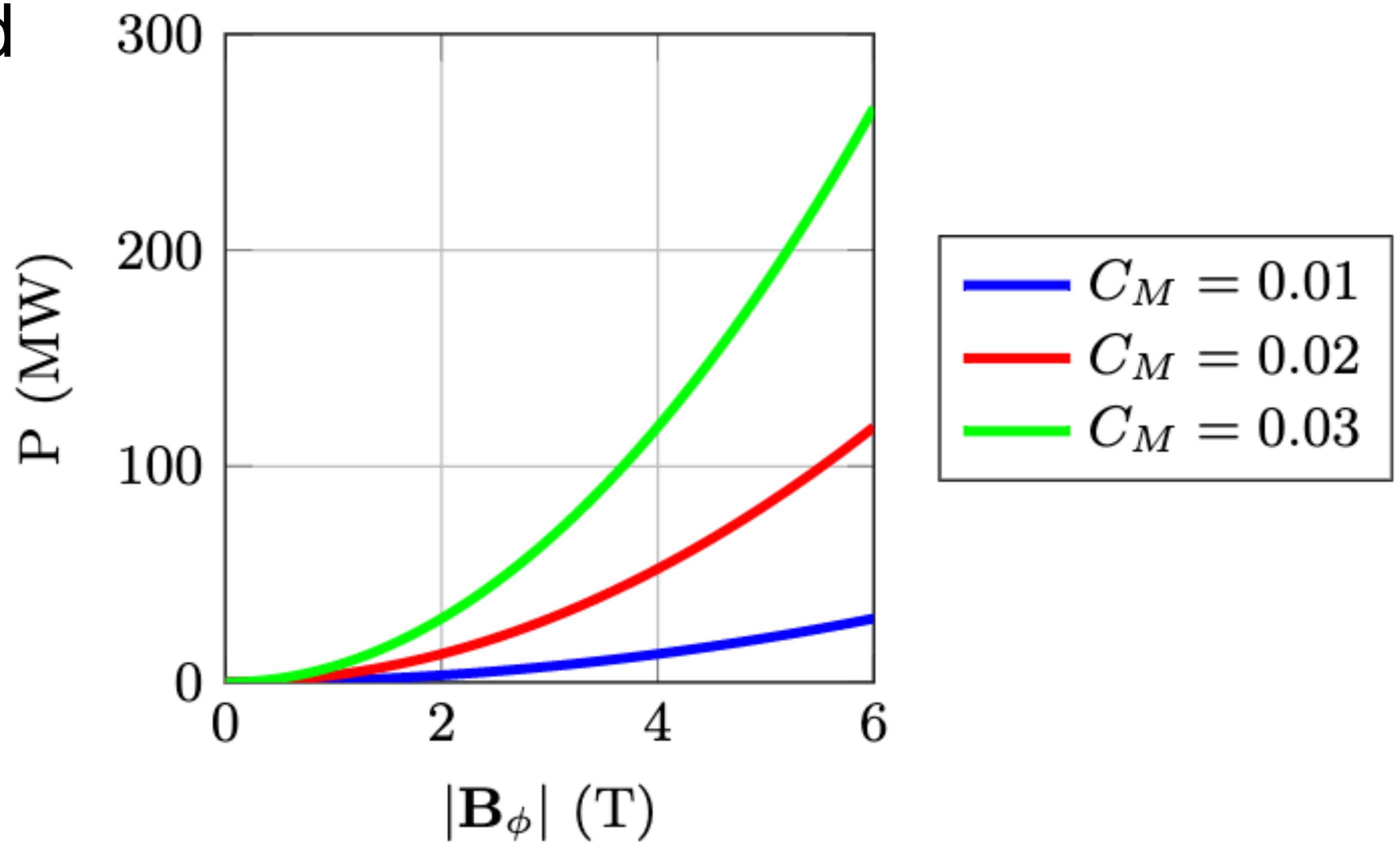


(d) Stream-wise currents for $I_0 = 50$ A. h is increased by a factor of 10.

Power requirements

- Balance between MHD drag and j×B thrust

- For an ITER-like reactor
  - Major radius ~ 6 m
  - Exposure length ~ 1 m
  - Liquid metal thickness ~ 1 cm
  - Flow speed to avoid evaporation
  - **500 MW output!**



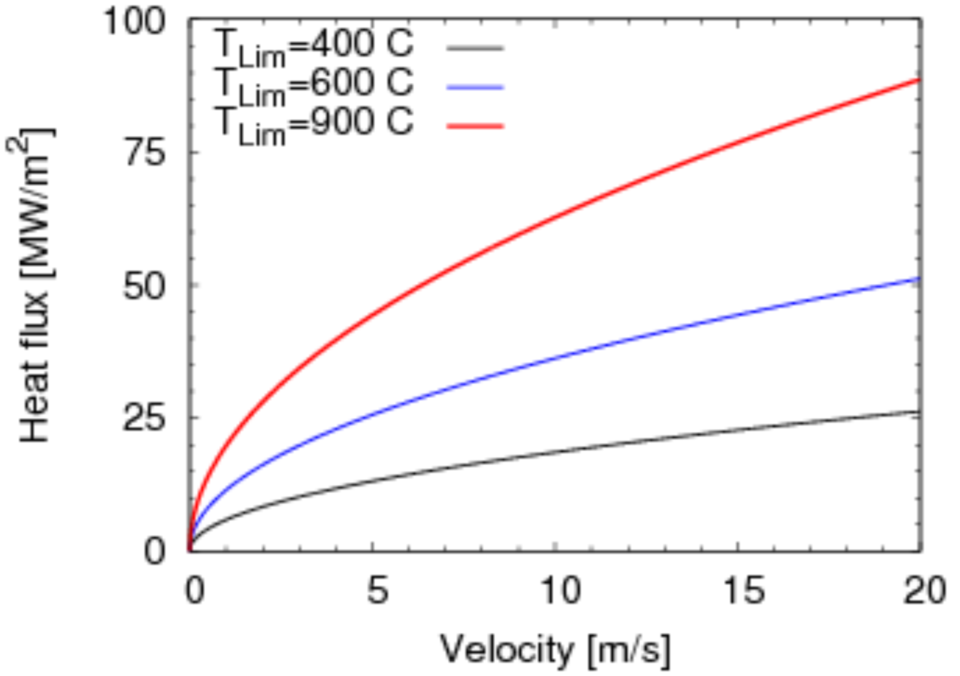
Power requirements for $L = 1$ m, $q_0 = 10$ MW/m^2.

Can we reduce flow-speed requirements?

- High-speed-liquid-metal-flow divertor present issues:
  - High power requirements
  - Flow detachment
- We need:
  - Smaller power requirements.
  - Smaller liquid lithium inventory.
  - Stable liquid metal flows.

$$v_{cr} = \frac{L}{t_{cr}}$$

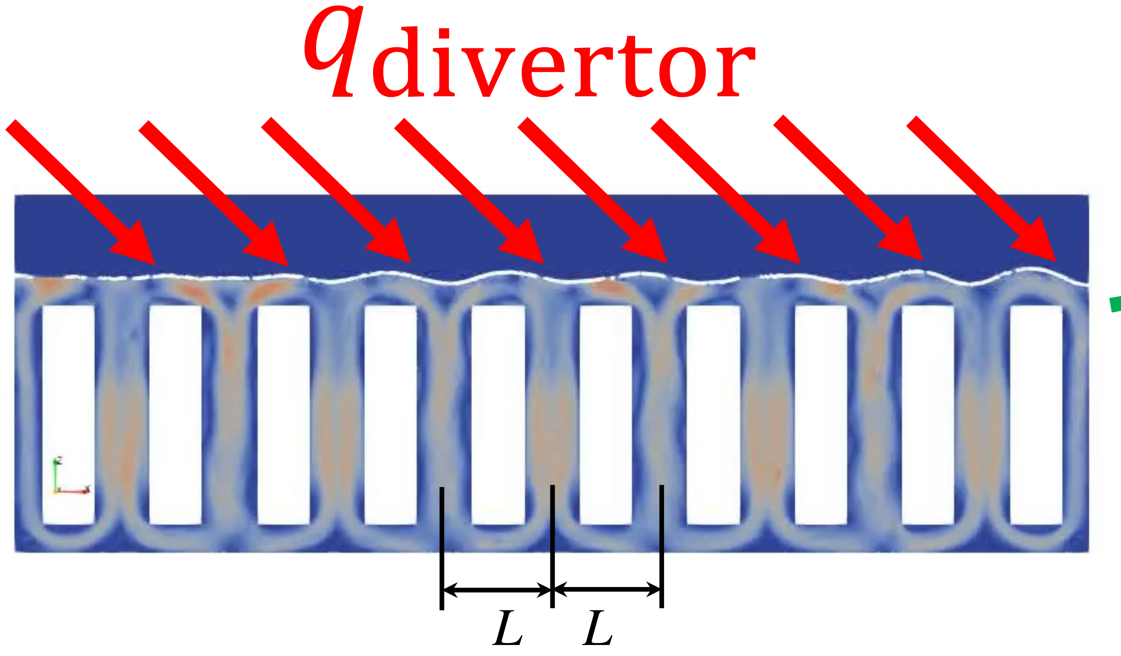
- **Solution: Alternative designs**

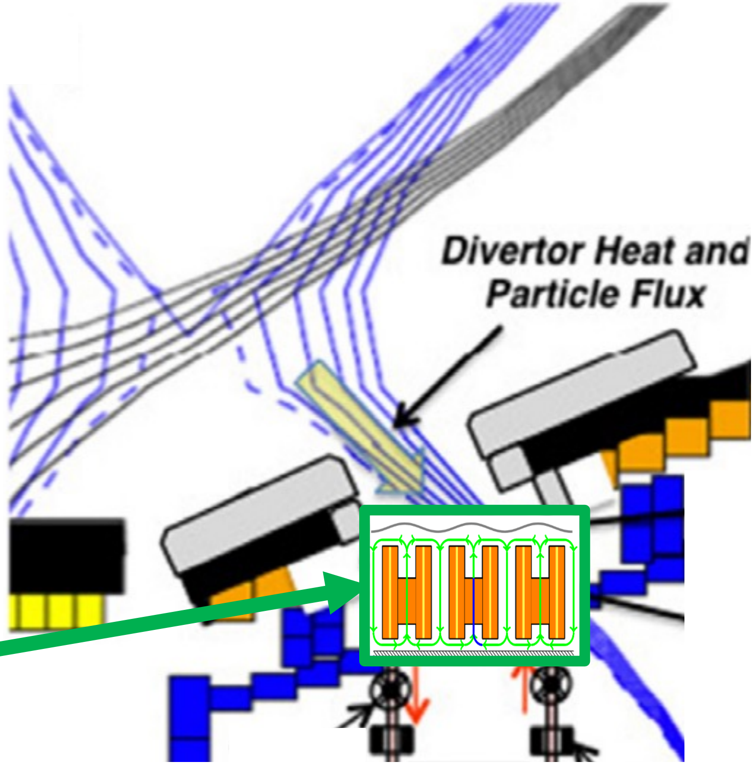


Jaworski [NF, 2017]

Divertorlets

- Smaller L leads to smaller speed requirements.
- Reduction of MHD drag, viscous drag, and splashing.

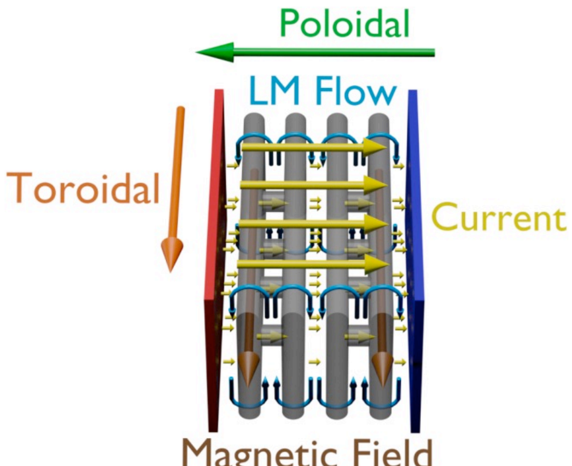




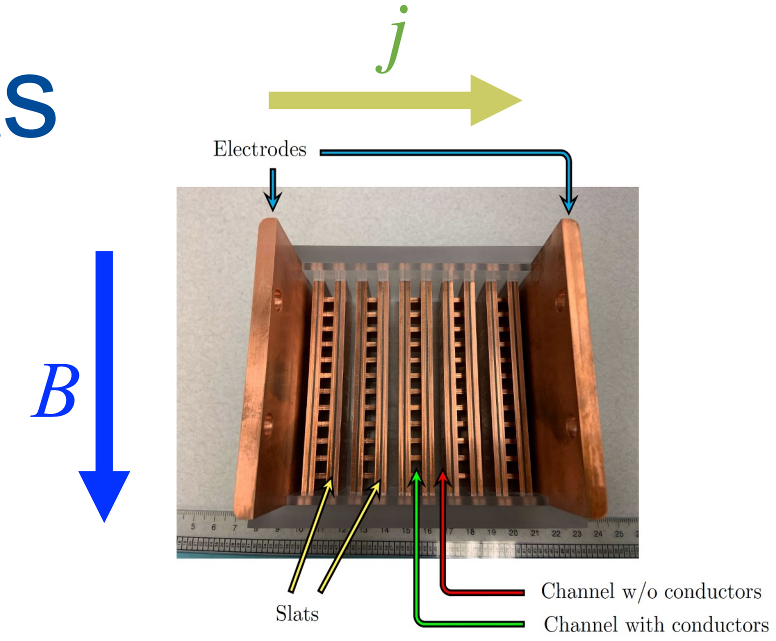
Operational principle of divertorlets

- Lorentz forces pump the flow.

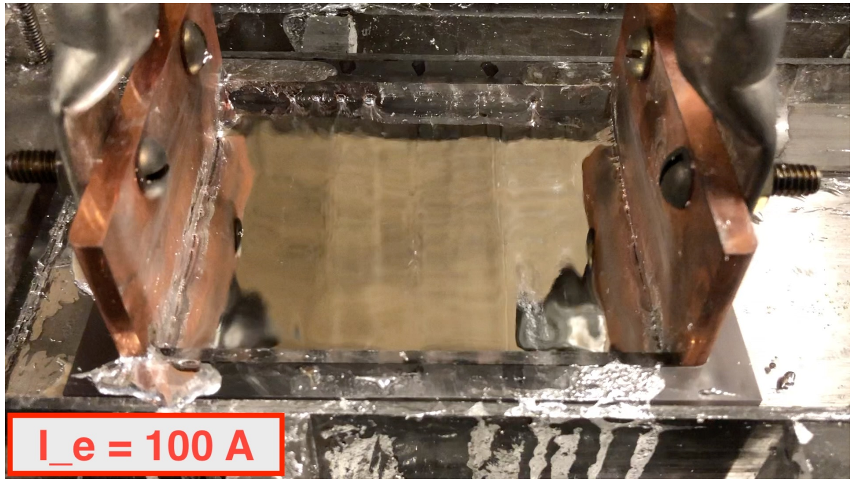
- Balance between:
    - $\mathbf{j} \times \mathbf{B}$ pumping
    - MHD drag $\sim C_M \sigma |\mathbf{U}||\mathbf{B}|^2$
    - viscous drag $\sim C_D \rho |\mathbf{U}|^2$



Fisher [NME, 2020]

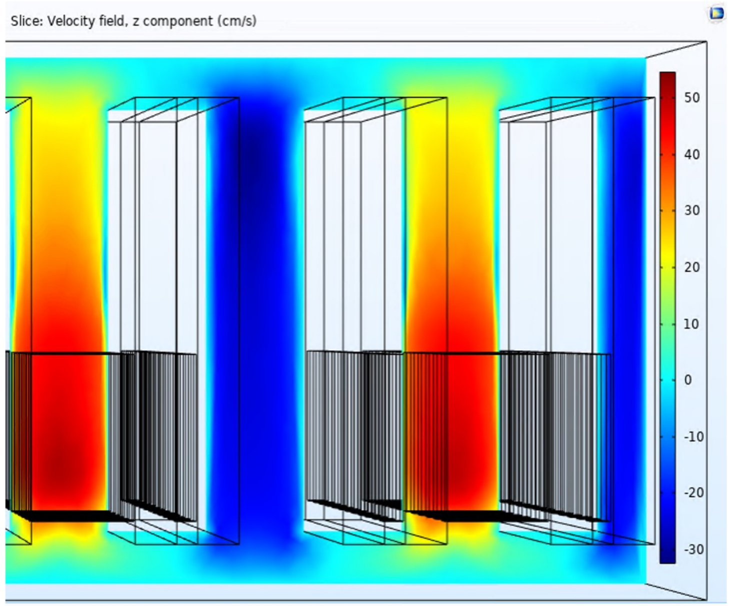


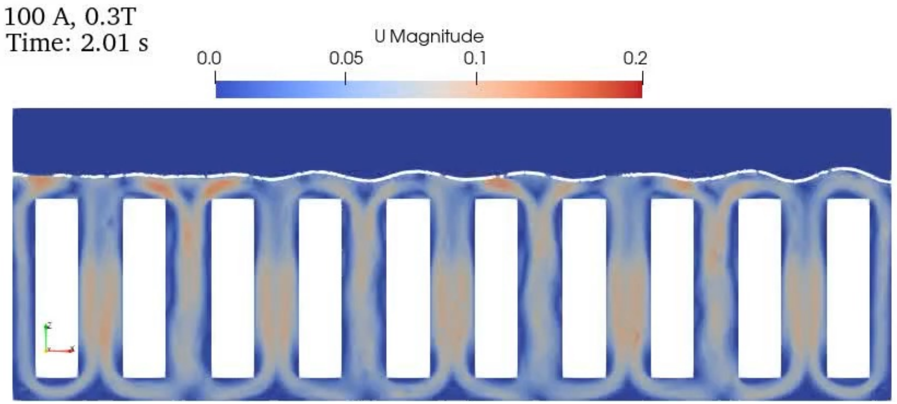
Top view

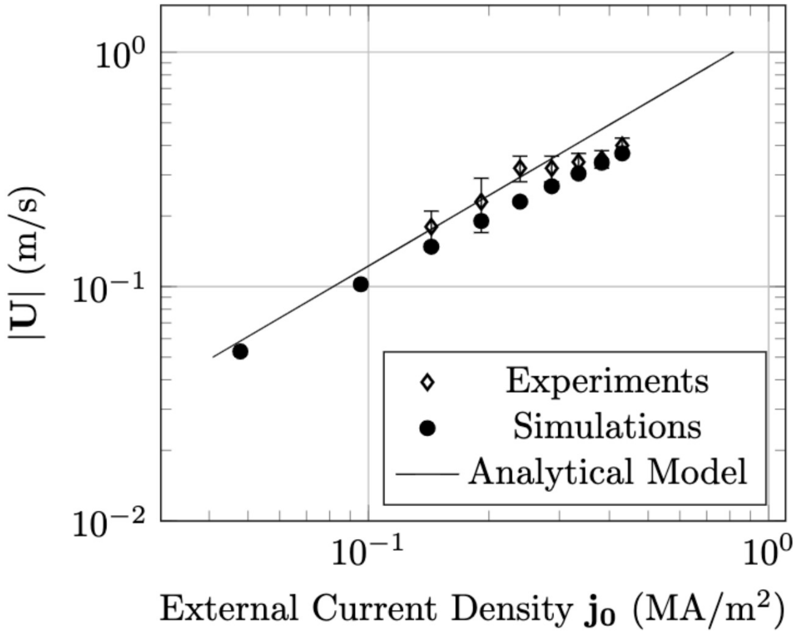


Simulations/Analytical review

- Simulations confirmed the desired flow loop around slats.
- Average upward velocities were compared to experimental results.



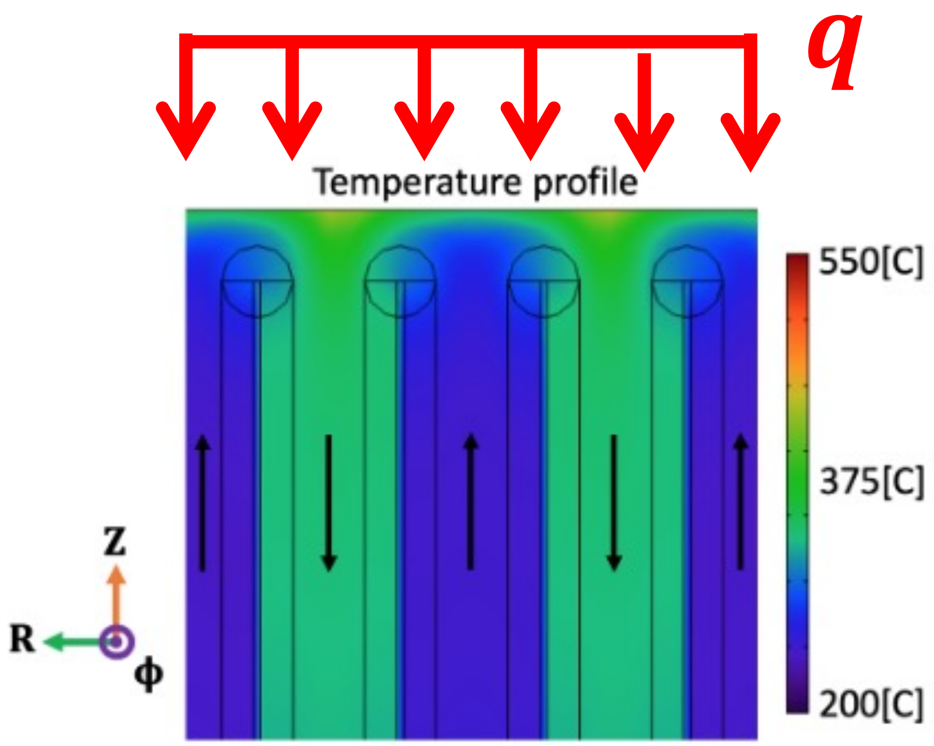




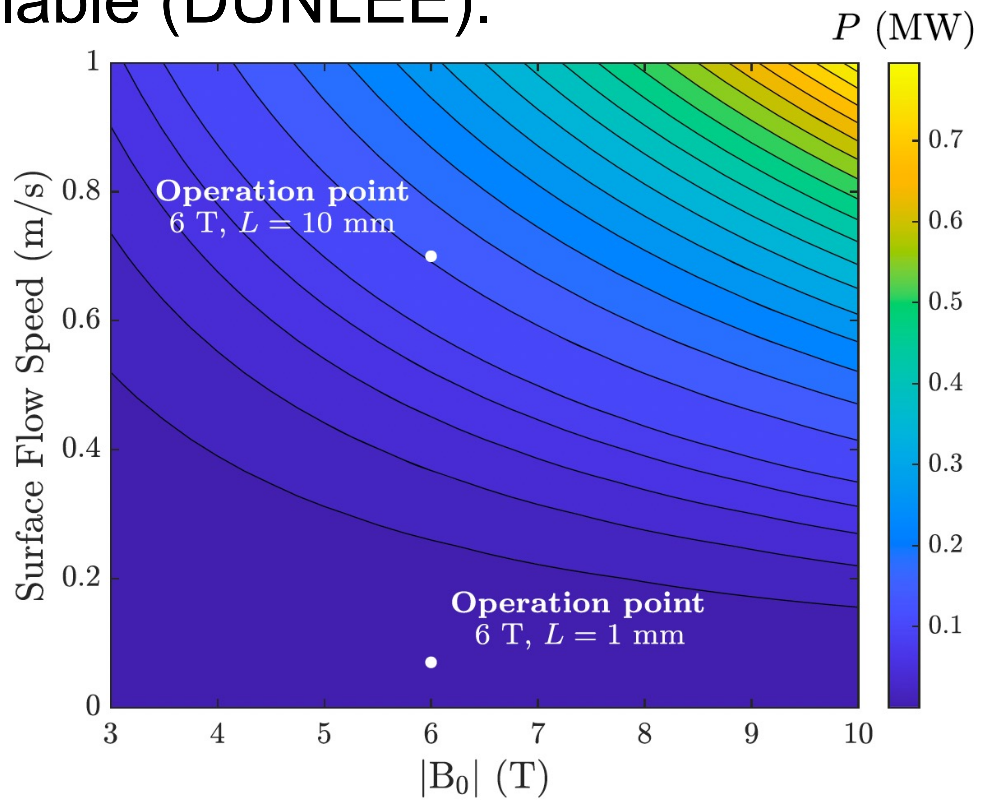
Saenz [NF, 2022]

Projections at the reactor scale

- 10 MW/m² uniform heat load.
- Liquid lithium below 450˚C.
- Less than 1% of power output of DEMO (500 MW).
- 100-micron tungsten 3D printing capability available (DUNLEE).



Fisher [NME, 2020]



Saenz [NF, 2022]

Summary

- Liquid metal flows encounter MHD drag when subject to magnetic fields, which generate piles of liquid metal on free-surface flows.
- Liquid metals could be propelled with external currents, but systems are sensitive due to fringing currents/flow detachment and power requirements are excessive.
- Simulations of free surface liquid metal flows were executed and in agreement with experimental results.
- Slow flow liquid metal system may avoid aforementioned issues. The divertorlets concept is an alternative.
- A divertorlets prototype was built and tested in LMX-U. Experiments and simulations were reproduced with analytically reviewed.
- Projections of divertorlets are promising for reactor scenarios.

Thank you for your attention!

References

F. Saenz, Z. Sun, A. E. Fisher, B. Wynne, and E. Kolemen, “Divertorlets concept for low-recycling fusion reactor divertor: experimental, analytical and numerical verification,” Nucl. Fusion, vol. 62, no. 8, p. 086008, Aug. 2022, https://doi.org/10.1088/1741-4326/ac6682

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A. E. Fisher, Z. Sun, and E. Kolemen, “Liquid metal ‘divertorlets’ concept for fusion reactors,” *Nuclear Materials and Energy*, vol. 25, p. 100855, Dec. 2020, doi: 10.1016/j.nme.2020.100855.

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Yang, J-C., T-Y. Qi, D-W. Ren, M-J. Ni, B-Q. Liu, J-S. Hu, and J-G. Li. "Magnetohydrodynamic effects on liquid metal film flowing along an inclined plate relating to plasma facing components." Nuclear Fusion 60, no. 8 (2020): 086003.

Research collaboration

- Francisco Saenz (PU): Experiments/Simulations

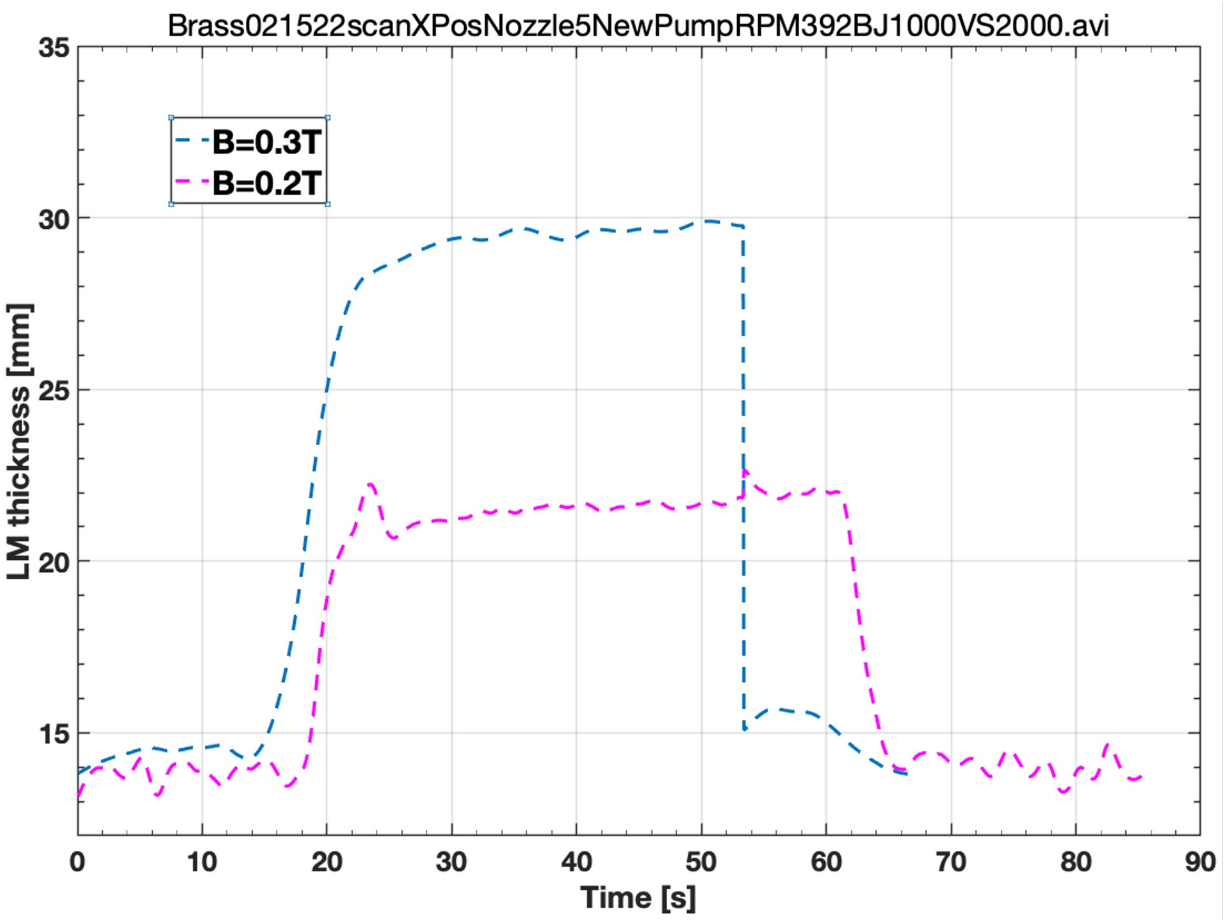
- Zhen Sun (PPPL): Experiments.

- Brian Wynne (PU): Experiments.

- Jabir Al-Salami (Kyushu U.): OpenFOAM.

$|\mathbf{B}|$ affects liquid-metal pileup

- $\mathrm{F_{MHD}} \sim C_M \sigma |\mathbf{U}||\mathbf{B}|^2$
- Measurement location: $x = 85$ mm.
- Brass walls, $t_w = 2.43$ mm, $Q = 16.3$ L/min, Inlet height: 5 mm

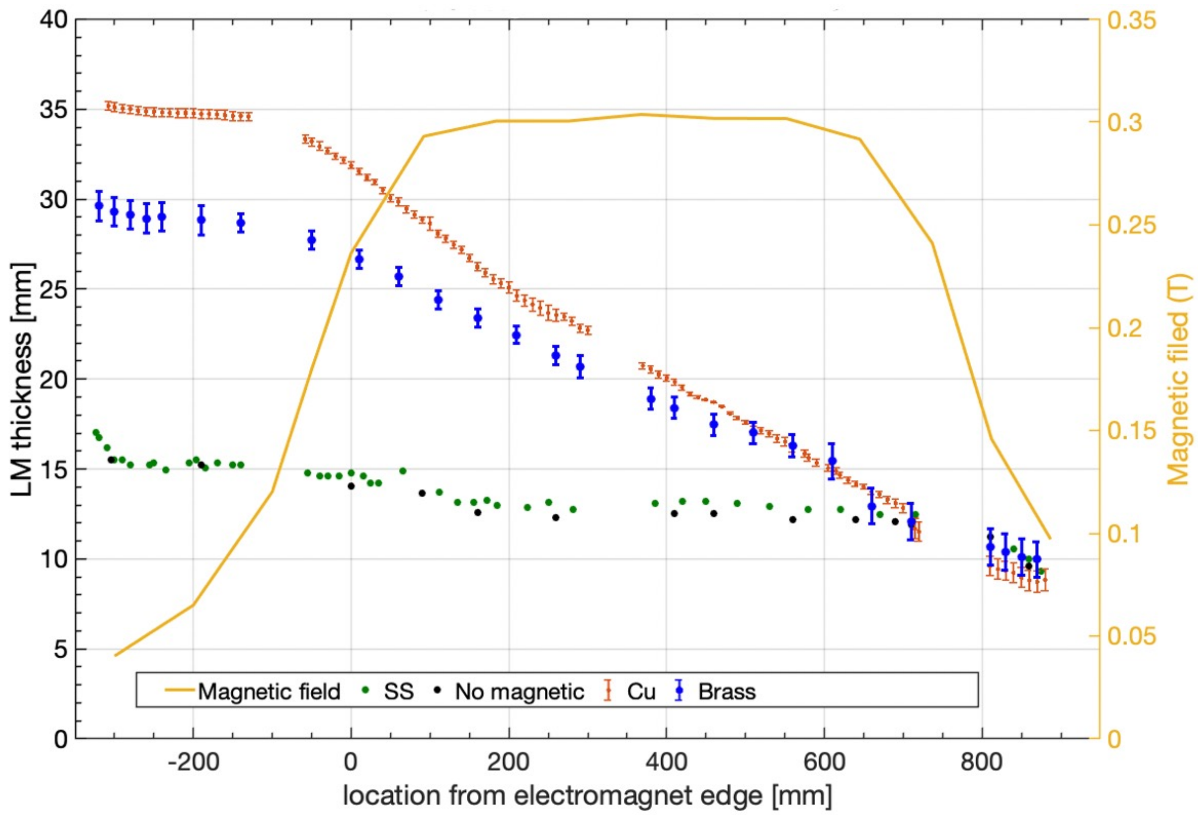


Wall conductivity is key for flow thickness

- $\mathrm{F_{MHD}} \sim C_M \sigma |\mathbf{U}||\mathbf{B}|^2$
- Wall conductivity ratio $c_w = \frac{t_w \sigma_w}{b\sigma}$
- Closed-pipe-flow equations:

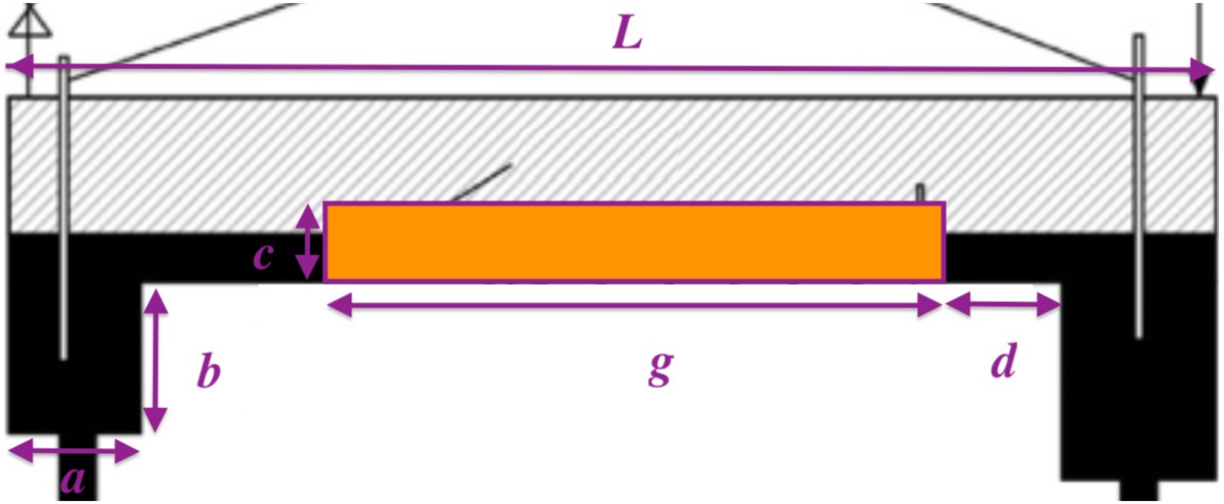
$$\Delta p = \lambda \frac{l}{2b} \frac{\rho U_m^2}{2} \qquad \frac{\lambda}{\lambda_0} = \frac{1}{3} \frac{c_w}{c_w + 1} Ha^2.$$

- c_w for different liners:
  - Cu: 0.9, Brass: 0.16, SS: 0.012
- B = 0.3 T, $Q = 16.3$ L/min, no nozzle.



j×B propulsion

- Oroshhi-2/NIFS/Kyoto University Collaboration.

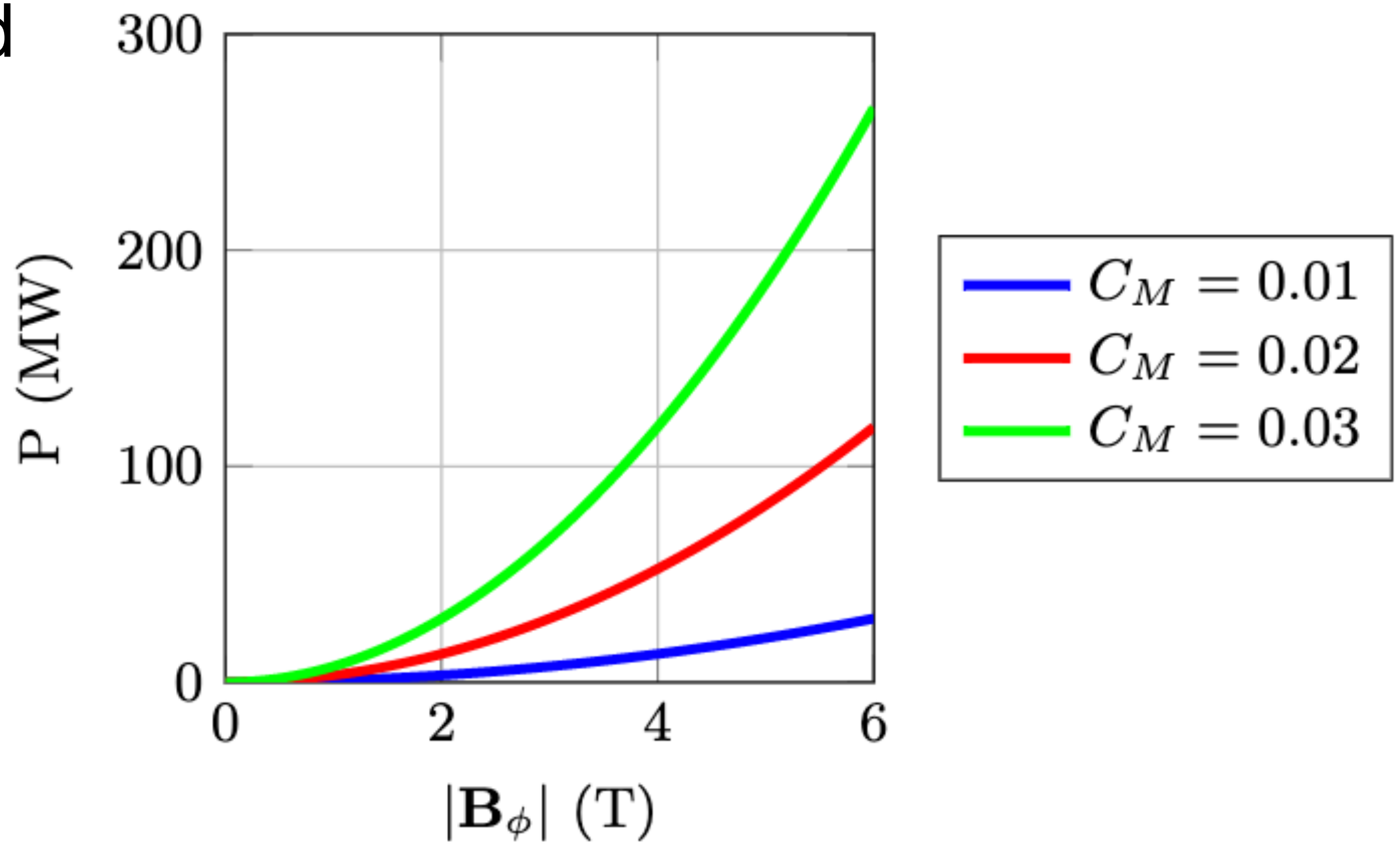


Power requirements

- Balance between MHD drag and j×B thrust

$$|\mathbf{j_e}| \sim \sigma C_M \frac{4Lq_0^2}{\pi k \rho c_p \Delta T^2} \frac{|\mathbf{B}_\phi + \mathbf{B_n}|^2}{|\mathbf{B_n}|}$$

- For an ITER-like reactor
  - Major radius ~ 6 m
  - Exposure length ~ 1 m
  - Liquid metal thickness ~ 1 cm
  - Flow speed to avoid evaporation

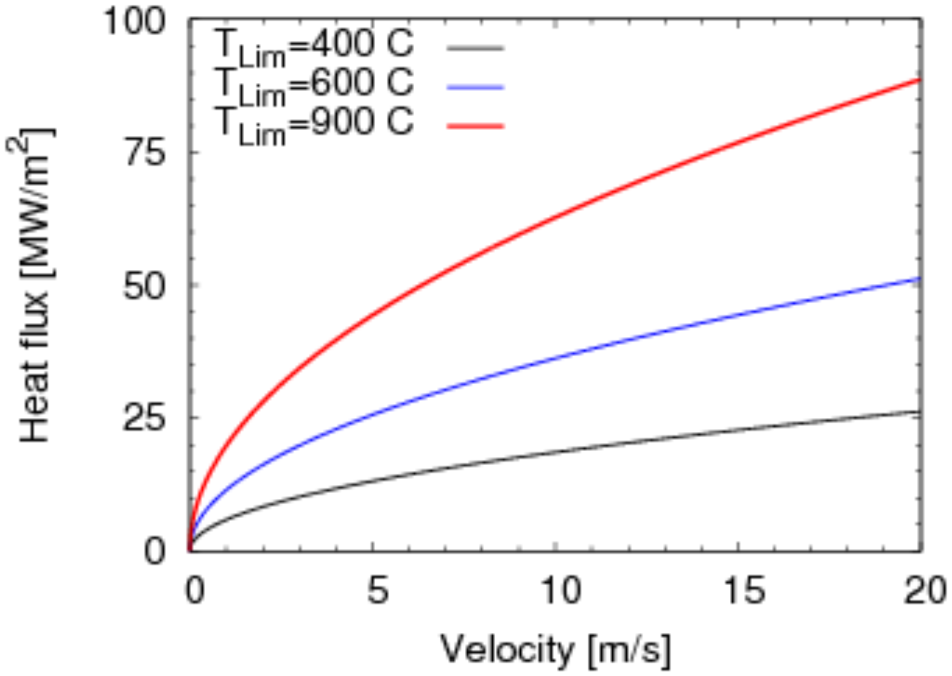


Power requirements for $L = 1$ m, $q_0 = 10$ MW/m^2.

Can we reduce flow-speed requirements?

- We need:
  - Smaller power requirements.
  - Smaller liquid lithium inventory.
  - Stable liquid metal flows.

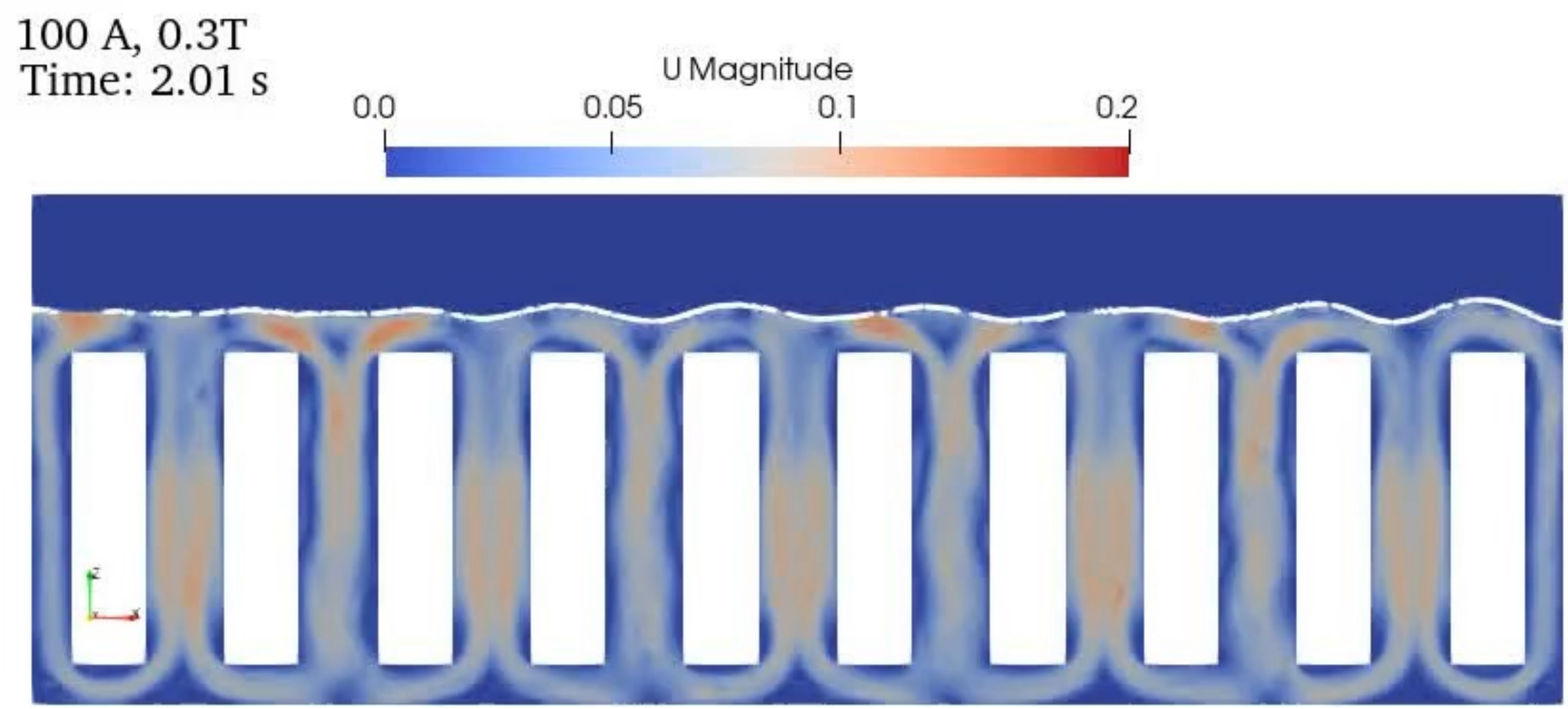
$$t_{cr} = \left(\frac{\Delta T}{2q}\right)^2 \pi k \rho c_p \qquad v_{cr} = \frac{L}{t_{cr}}$$



Jaworski [NF, 2017]

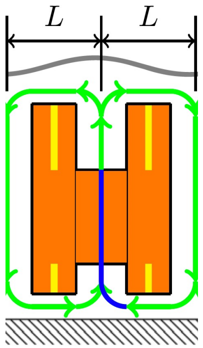
- **Solution: Alternative designs**

Divertorlets/OpenFOAM

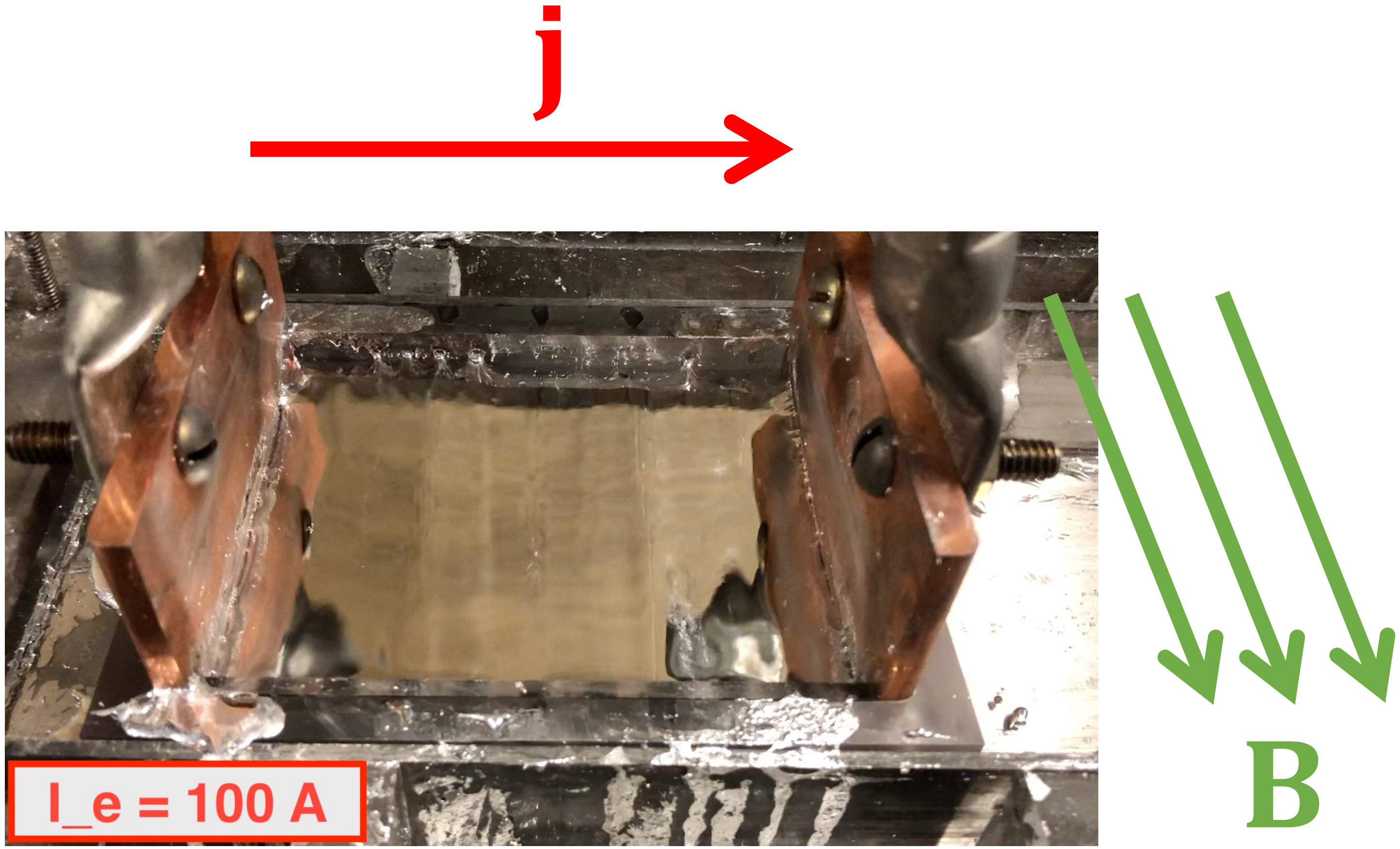


Experimental tests of divertorlets in LMX-U

- Peak-valley deformations on the free surface.
- Surface tension should increase with thinner channels and get rid of deformations.
- $L = 10$ mm

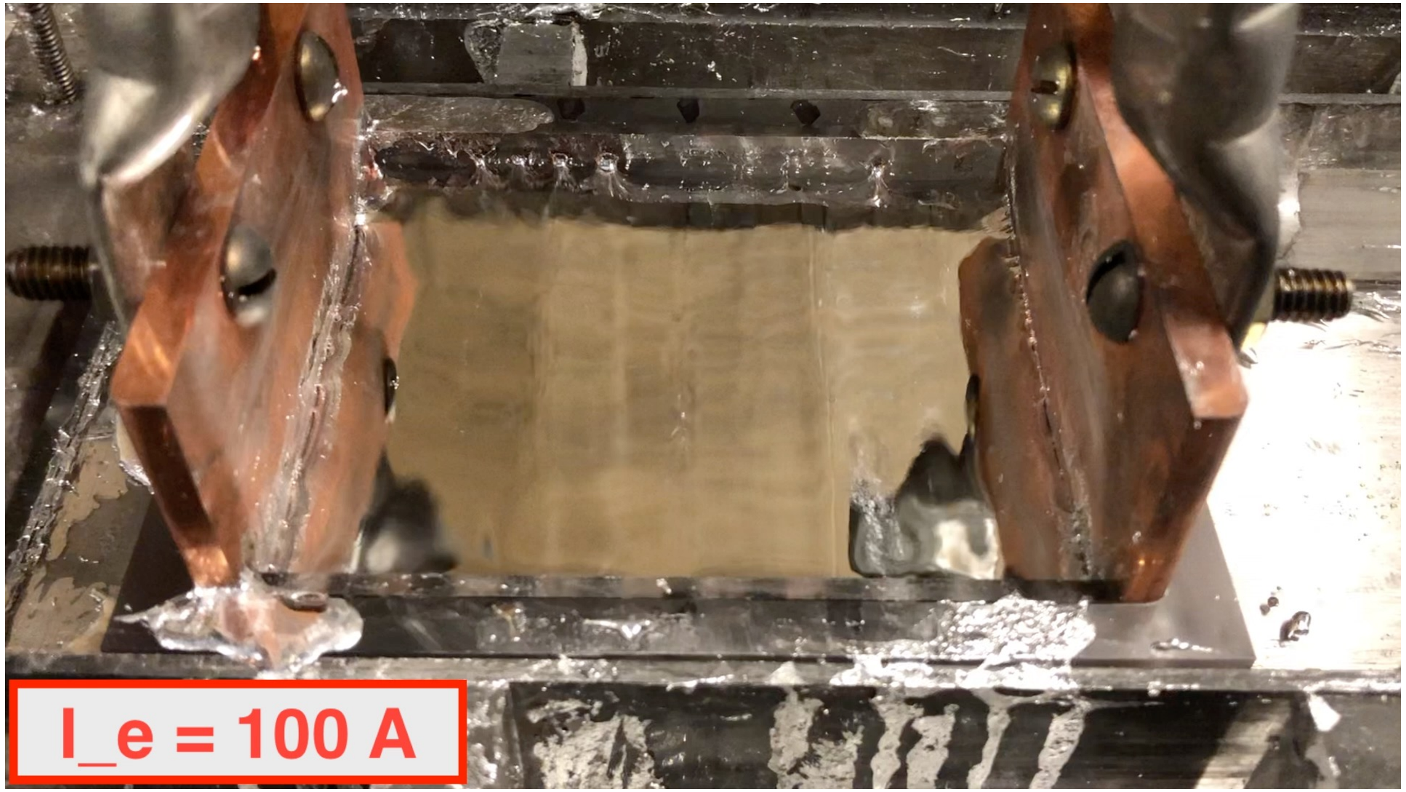


Saenz [NF, 2022]

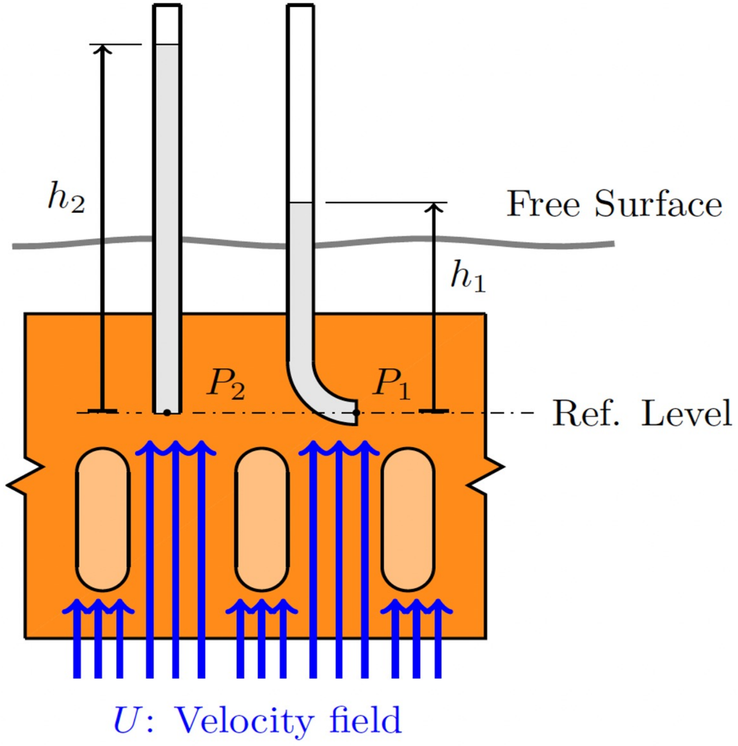


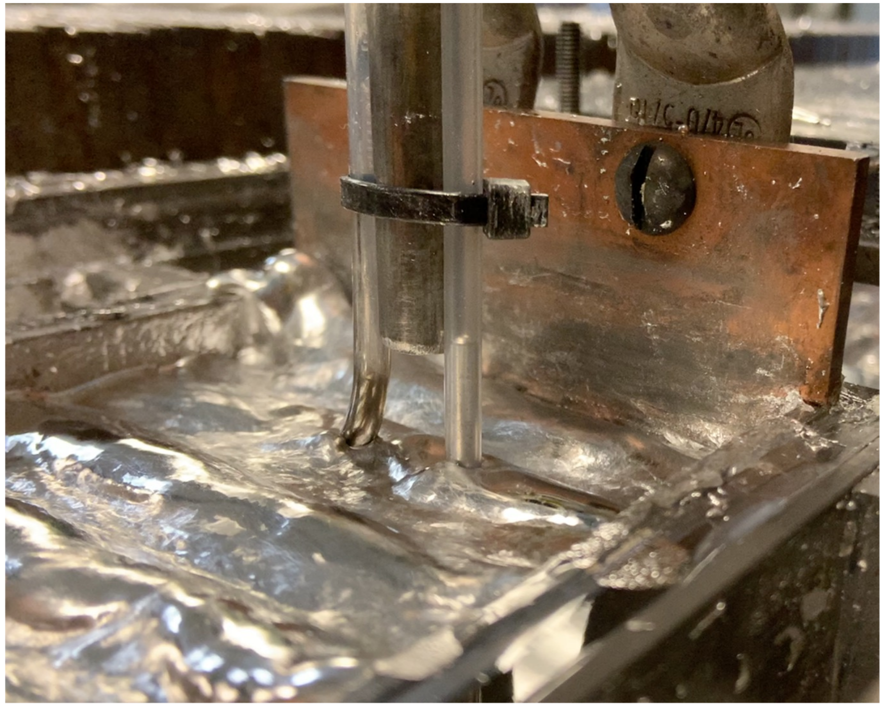
Experimental tests of divertorlets in LMX-U

- Peak-valley deformations on the free surface.



Experimental tests of divertorlets in LMX-U





$$P_1 + \frac{1}{2}\rho U^2 \approx P_2 \quad \longrightarrow \quad \|\mathbf{U}\| \approx \sqrt{2g\Delta h}$$

Divertorlets/OpenFOAM

- 0.3 T, 600 A