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MHD liquid-metal-flow experiments and simulations for nuclear fusion applications.

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Research collaboration

- Francisco Saenz (PU): Experiments/Simulations

- Zhen Sun (PPPL): Experiments.

- Brian Wynne (PU): Experiments.

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

- Andrei Khodak (PPPL): ANSYS.

- Sergey Smolentsev (Oak Ridge): FORTRAN.

Overview

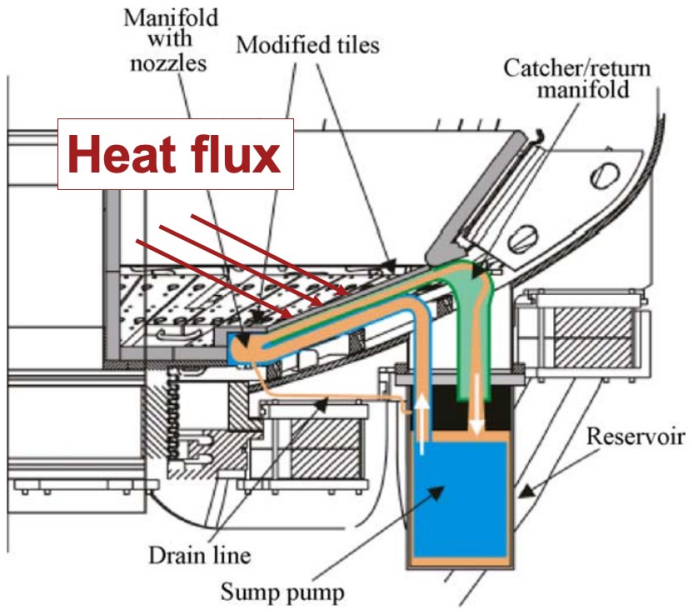
- **Motivation and description of LMX-U.**
- **Liquid metal flows in open channel**:
  - Experiment and simulations.
  - Operational advantages and issues.
- **Divertorlets**:
  - Experiment and simulations
  - Projections.

Motivation

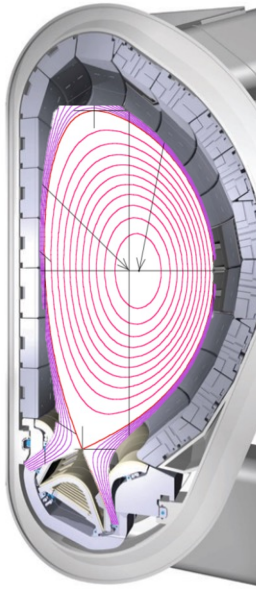
- Liquid metal flows for heat exhaust in divertors of fusion reactors.

- 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.



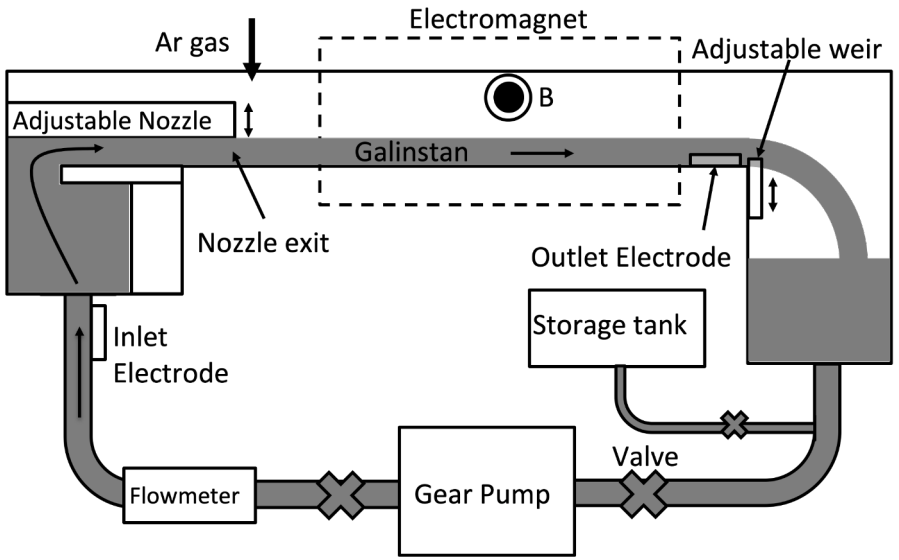
Ying [FED, 2004]

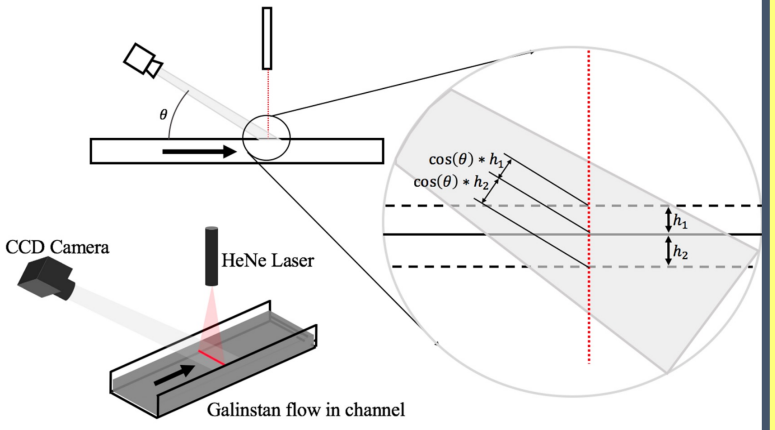


Liquid Metal R&D without plasmas

- **Aim**: To understand liquid metal flows at small scale.

- **New Divertor Ideas:** j×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
  - Height-adjustable nozzle at inlet allows inlet depth to be changed:
    - Max. flow speed: 2 m/s
    - Removable nozzle
  - Channel liner: acrylic base. Width: 109 mm
  - Inclination angle range: 0˚ - 7˚.
  - Movable channel.



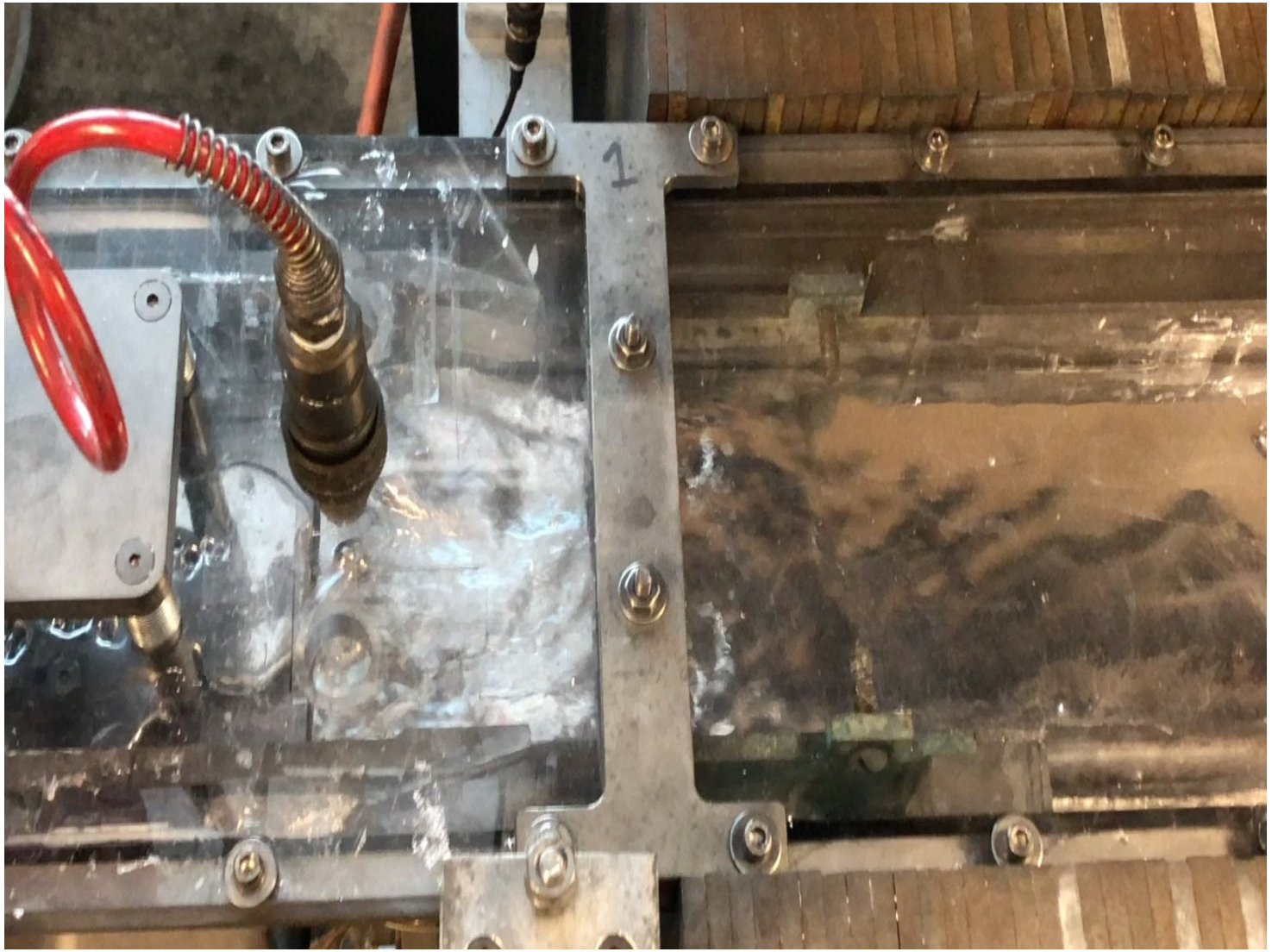


Hvasta [NF, 2018]

LMX-U publications by Kolemen group:

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)

Free Surface LM Flow in LMX-U Channel

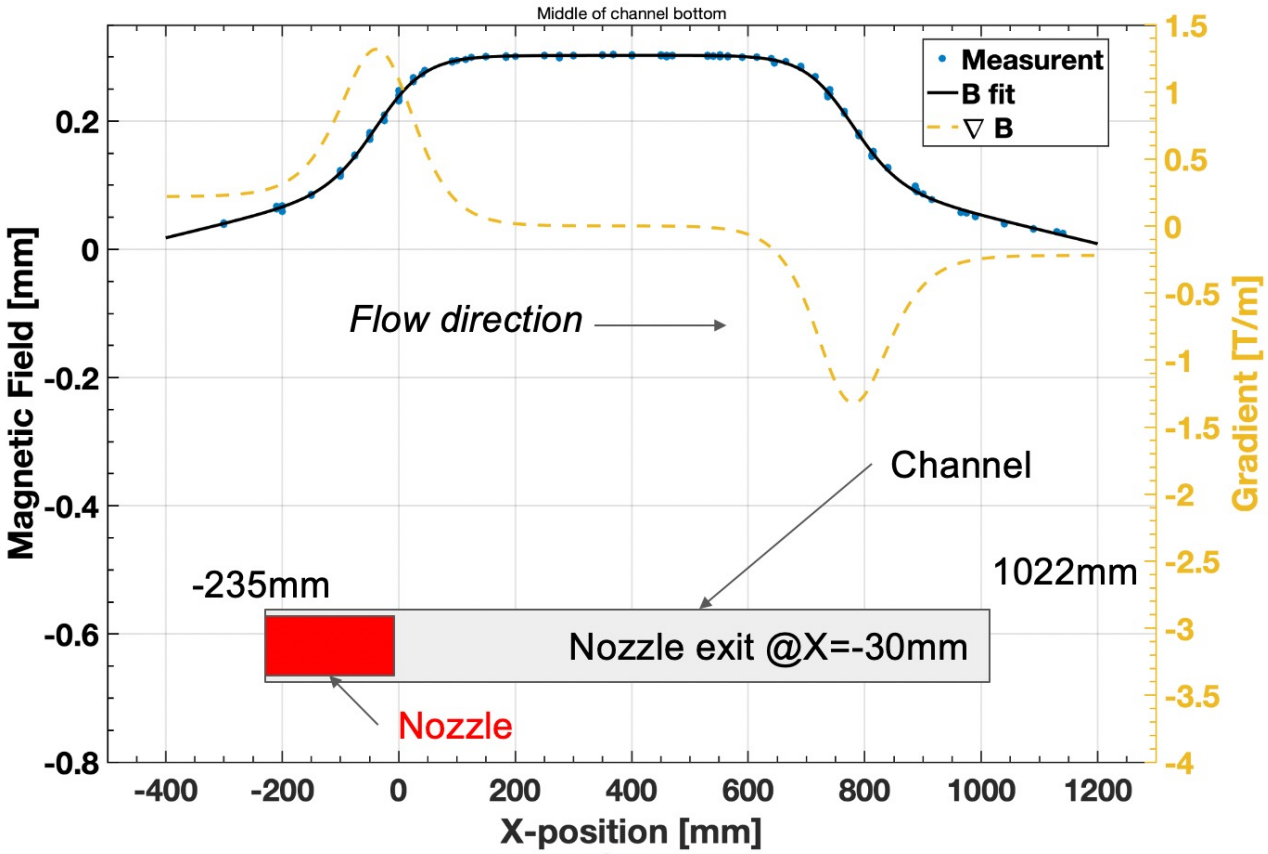


MHD drag on liquid metal flows

- $\mathrm{F_{MHD}} = \sigma\,(\mathrm{E} + \mathrm{U}\times\mathrm{B})\times\mathrm{B} \sim C_M \sigma |\mathbf{U}||\mathbf{B}|^2$

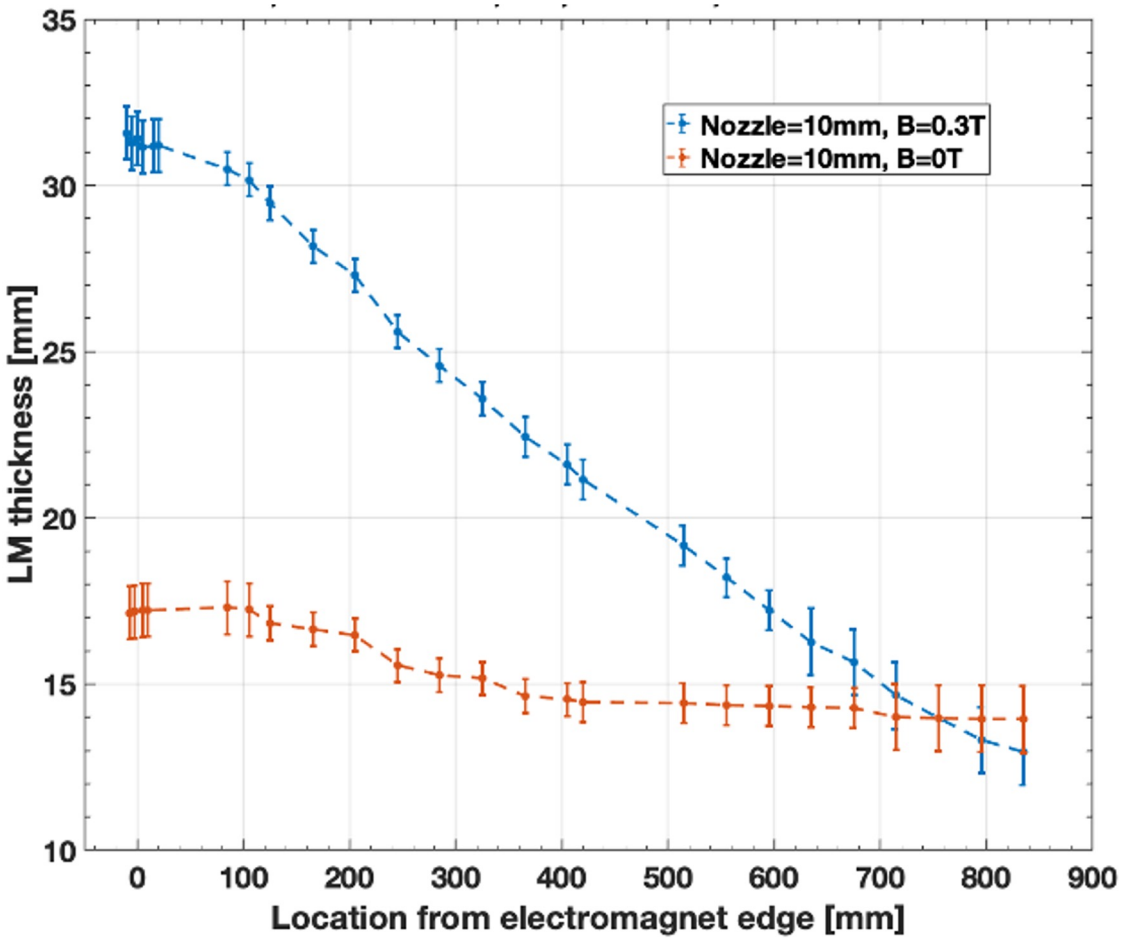
- Different conductive boundaries:
  - Cu: 58.7 MS/m, 2.36 mm wall thickness
  - Brass : 17 MS/m, 1.6 mm wall thickness.
  - AISI 316 (SS): 1.32 MS/m.

- Electromagnetic edges: 0 mm – 740 mm



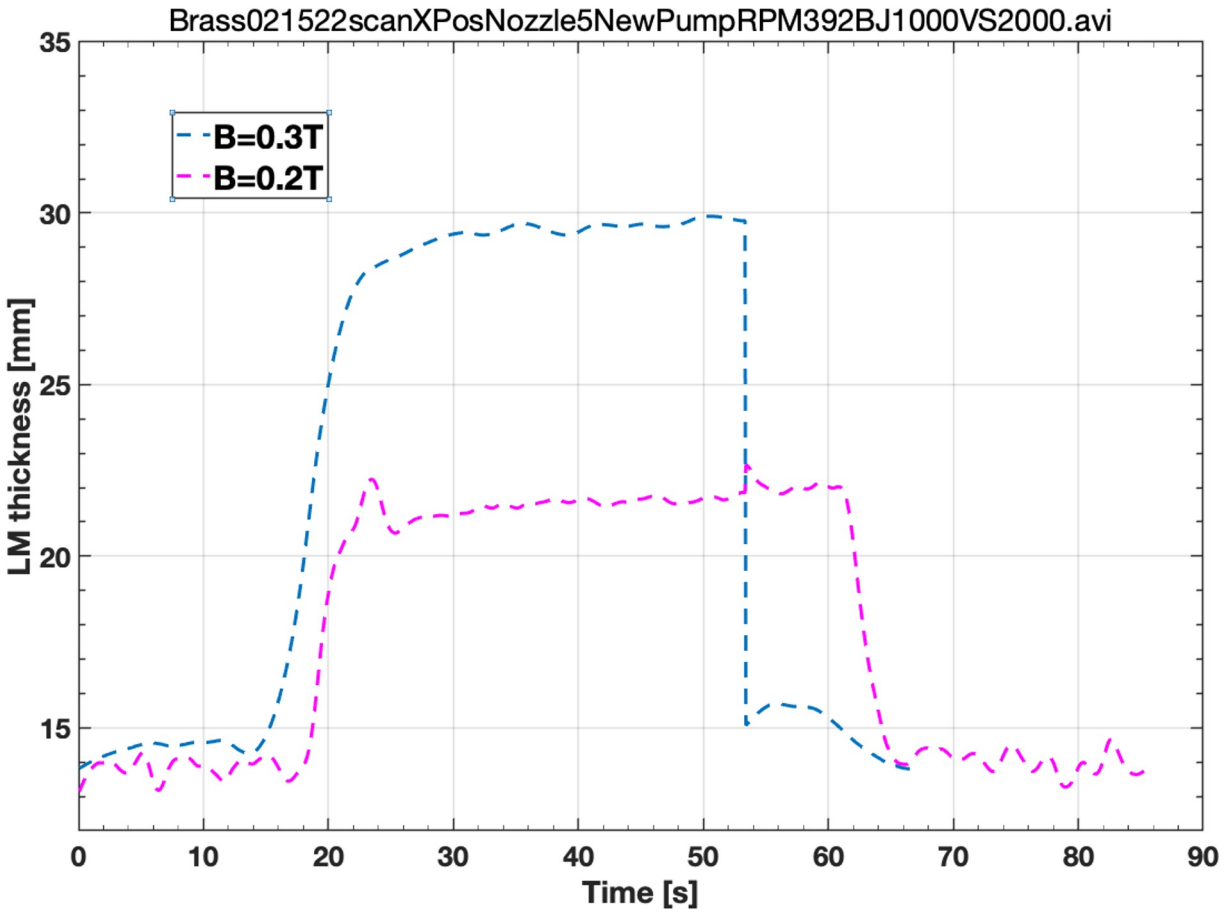
MHD drag experiments

- Max. nozzle gap: 10 mm, nozzle exit position: x =-30 mm.
- Q = 16.3 L/min, brass walls, t_w = 1.6 mm.
- Hydrodynamic flow (0 T)
  - Re ~ 5200; Fr = 0.82 (nozzle), 0.37 (x = 85 mm)
- B = 0.3 T
  - Ha ~ 590, Re ~ 4270



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

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

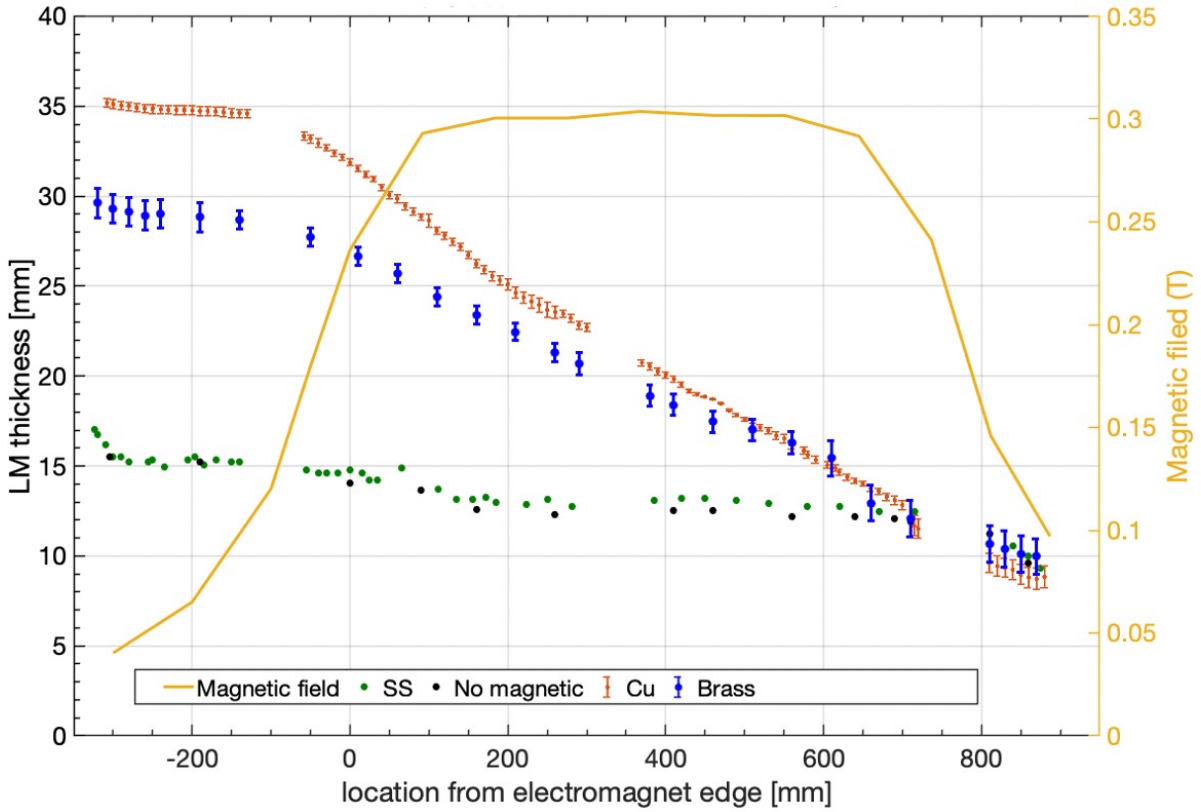


Wall conductivity is key for flow thickness

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

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

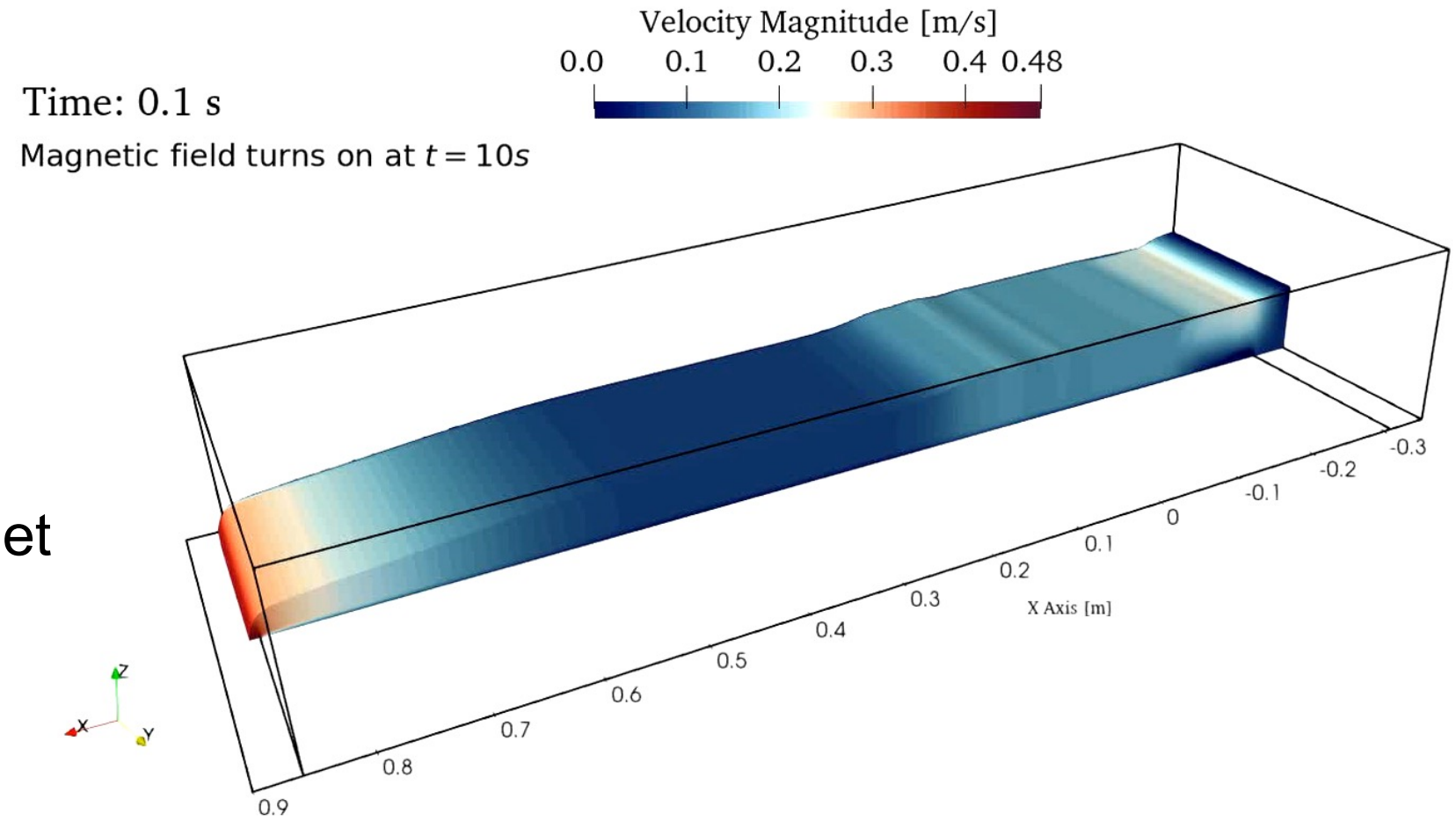
- c_w for different liners:
  - Cu: 0.9, Brass: 0.16, SS: 0.012
- B = 0.3 T, $Q = 16.3$ L/min, no nozzle.



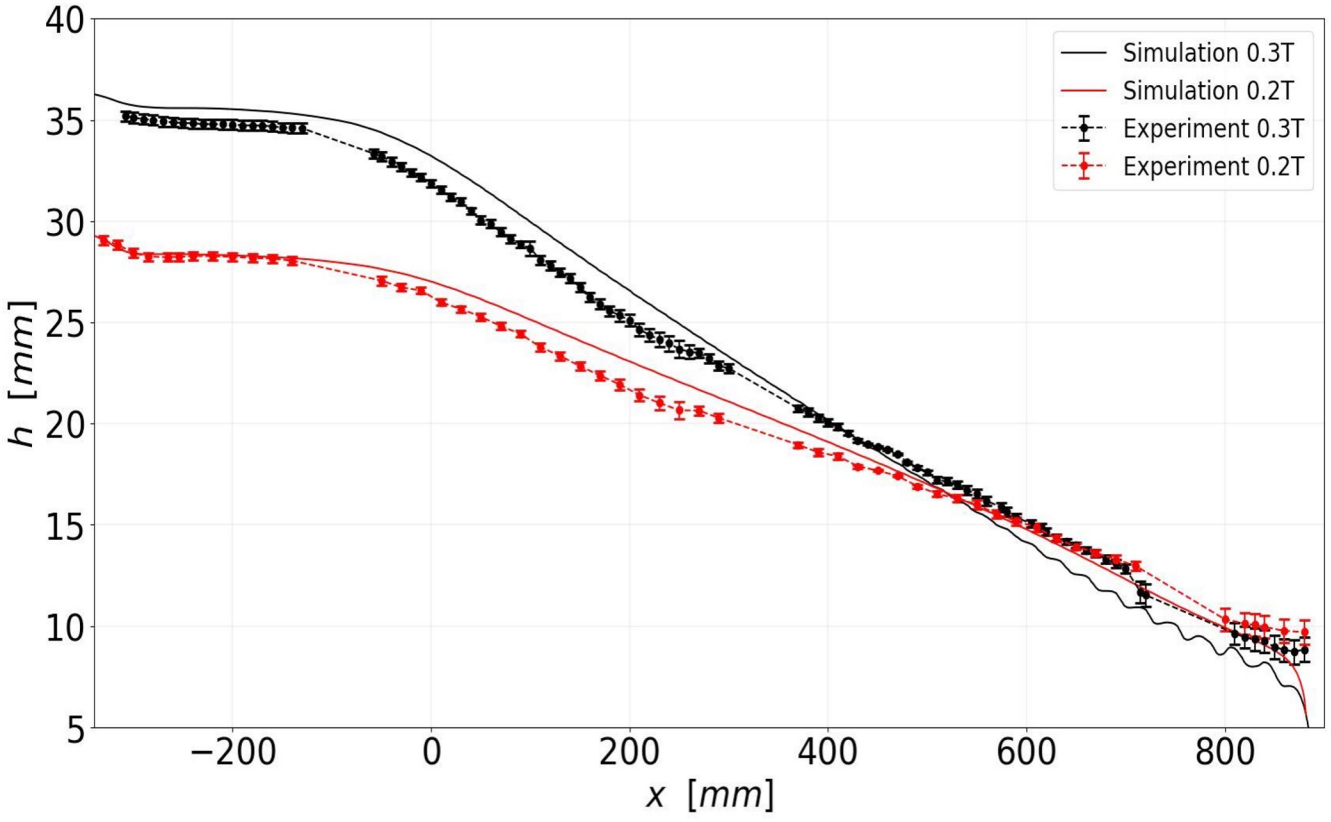
Simulations

- **OpenFOAM:**
  - **Full 3D MHD**

- Parameters:
  - $Q = 16.3$ L/min
  - $t_w = 2.36$mm
  - Cu walls
  - No nozzle for flow inlet

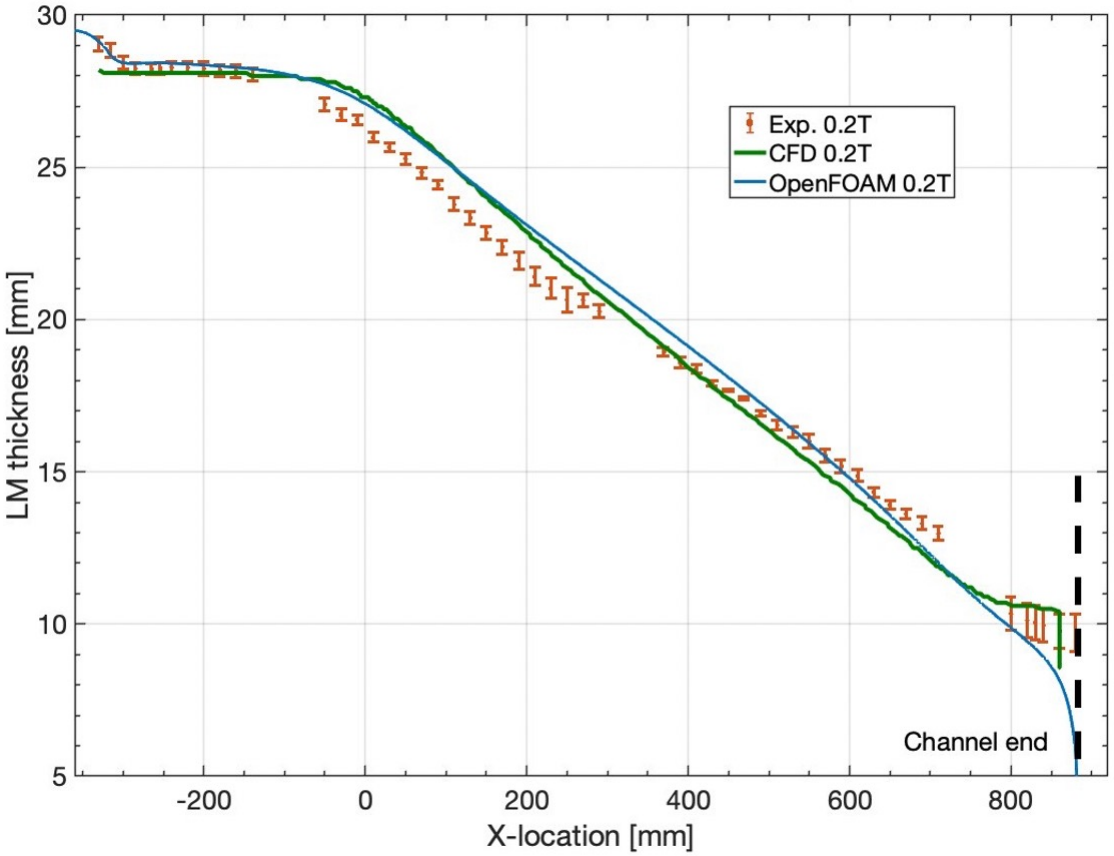


OpenFOAM



Credits to J. Al-Salami, Kyushu University

ANSYS CFX



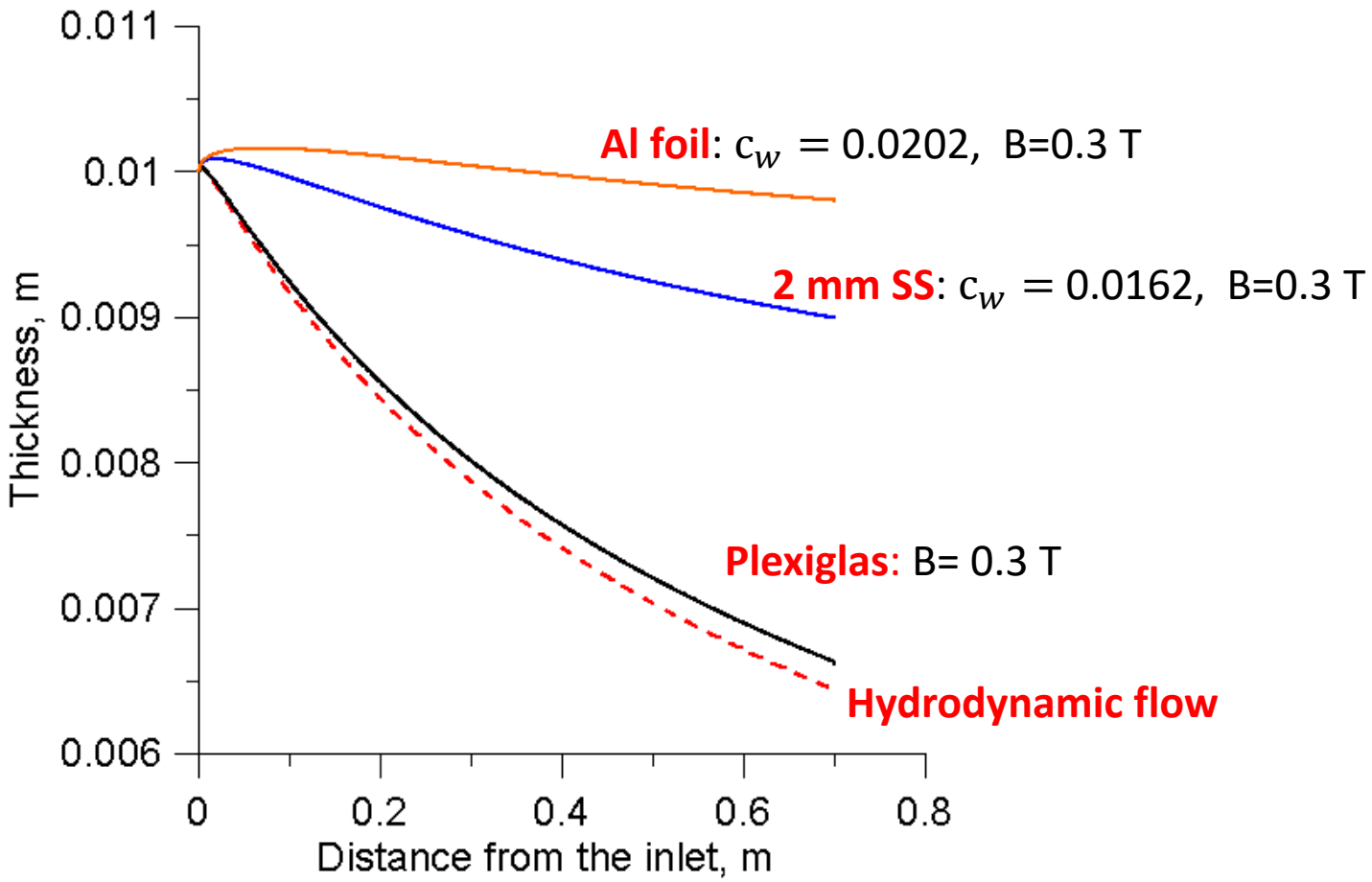
Credits to A. Khodak

- $t_w = 2.36$mm
- Cu walls
- No nozzle
- $Q = 16.3$ L/min
- Full 3D MHD.

Inclined-flow simulations (FORTRAN)

- Different wall conductivity ratios

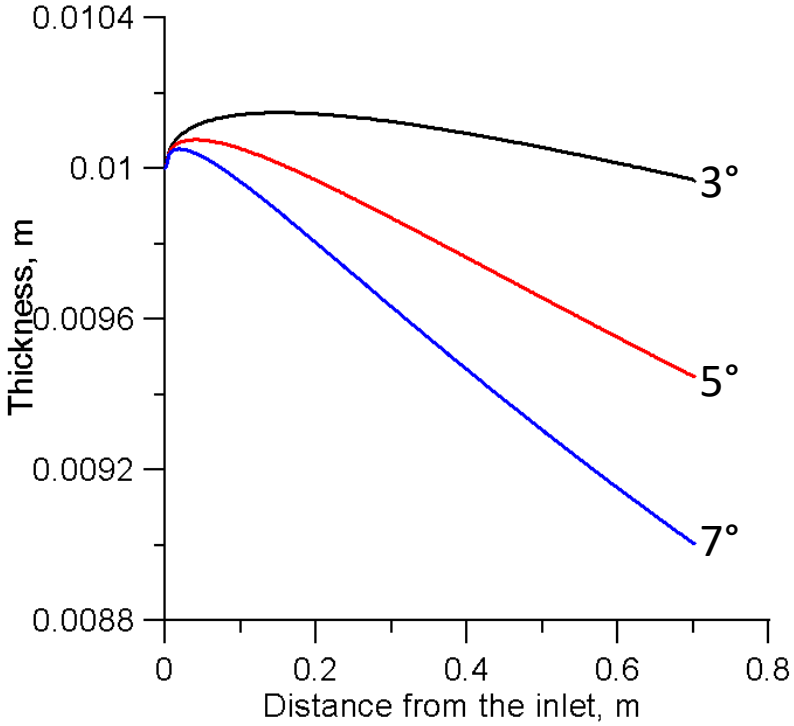
h_{in}=1 cm, U_{in}=1 m/s, L=0.7 m,
W=0.1 m, Alfa=7 Degree



Credits to S. Smolentsev.

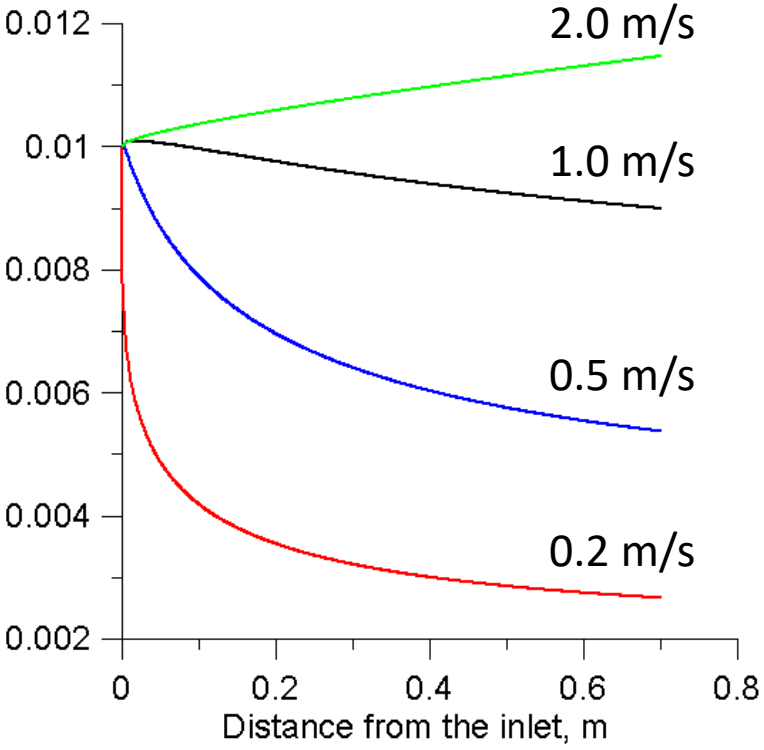
Inclination angle

B=0.3 T, U_{in}=2 m/s, L=0.7 m,
W=0.1 m, h_{in}=1 cm
Plexiglas



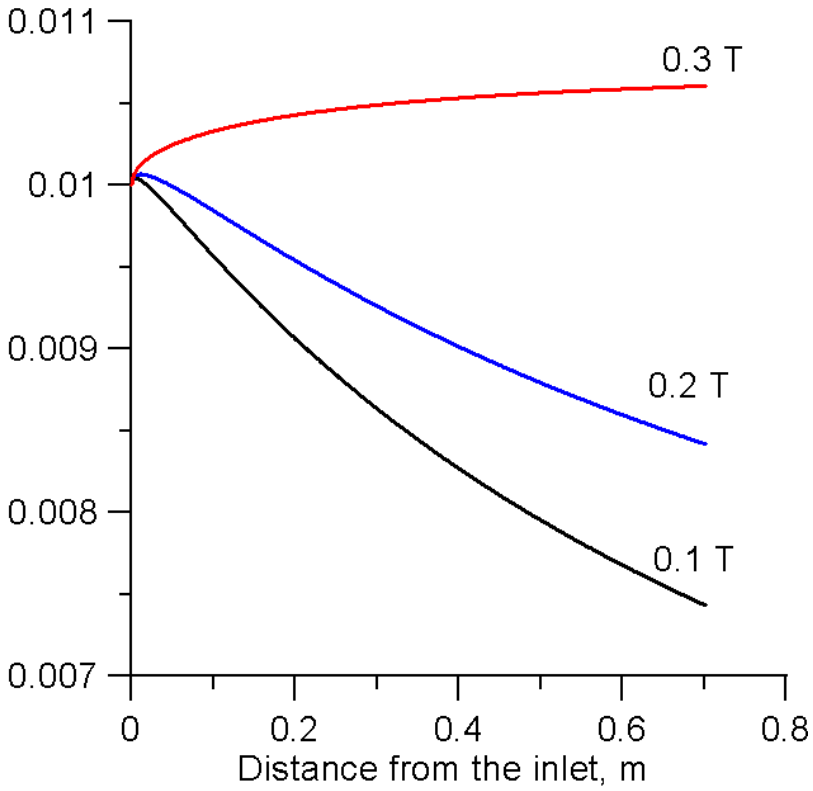
Inlet speed

h_{in}=1 cm, B=0.3 T, L=0.7 m,
W=0.1 m, Alfa=7 Degree
2 mm steel



B-field strength

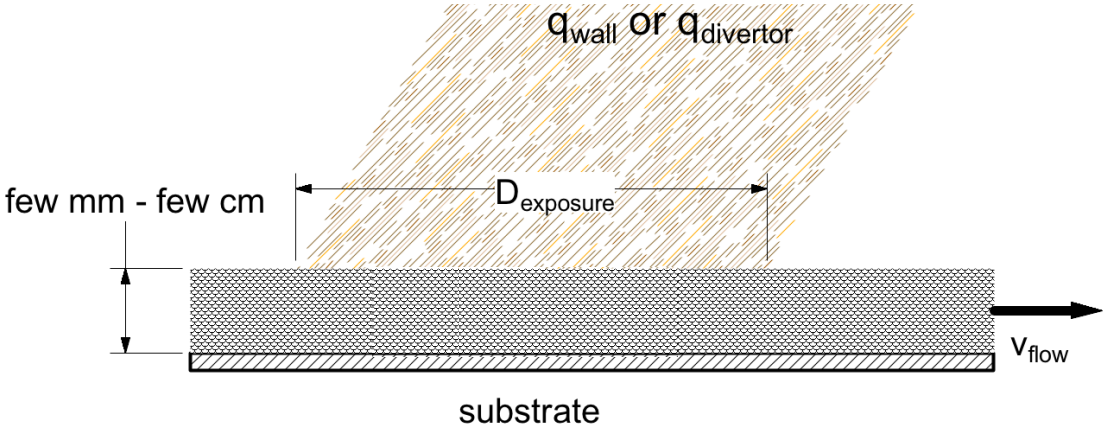
2 mm Steel, U_{in}=1 m/s, L=0.7 m,
W=0.1 m, h_{in}=1 cm, Alfa=5 Degree



Credits to S. Smolentsev.

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



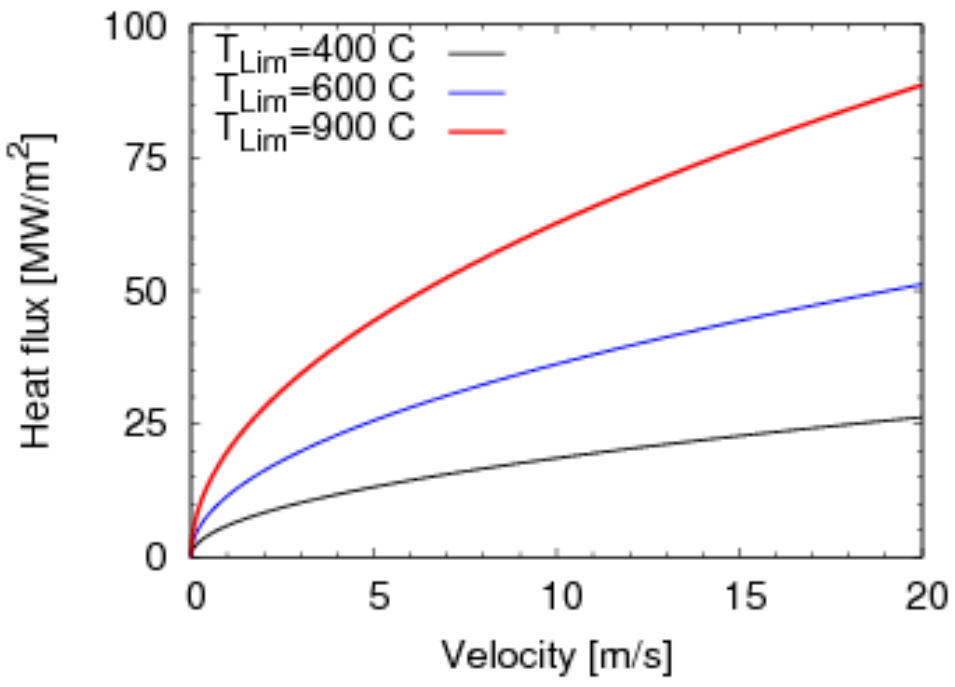
Kolemen [NME, 2019]

Can we reduce flow-speed requirements?

- Is it possible reduce the speed?
  - **Solution: Alternative designs**

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

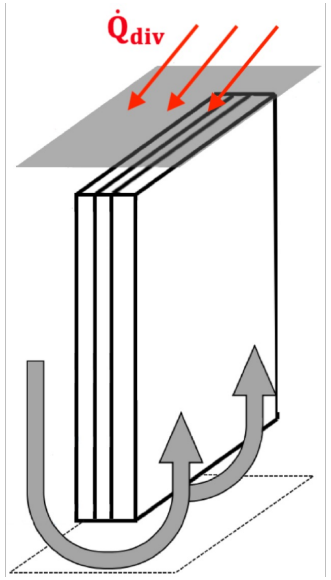
$$v_{cr} = \frac{L}{t_{cr}}$$

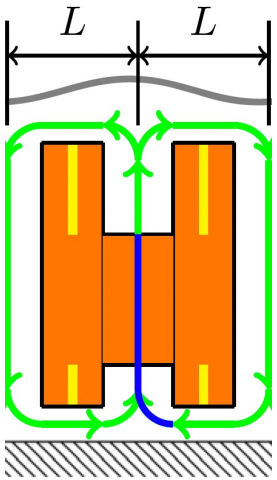


Jaworski [NF, 2017]

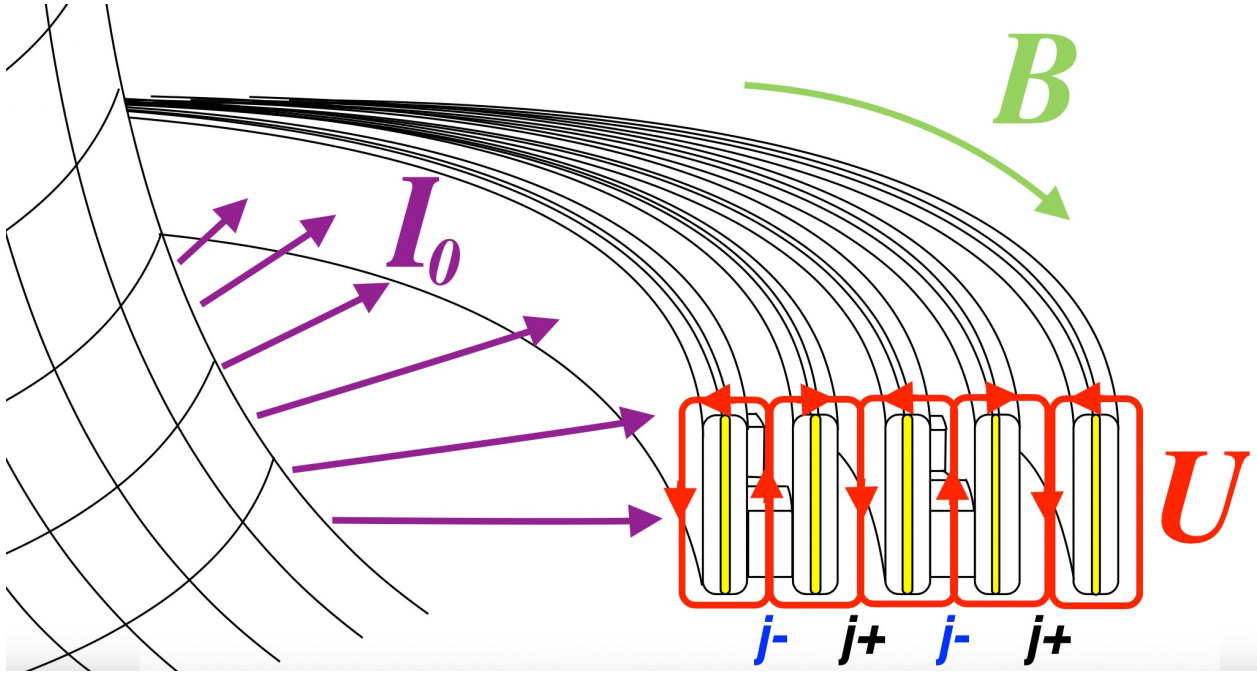
Divertorlets

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



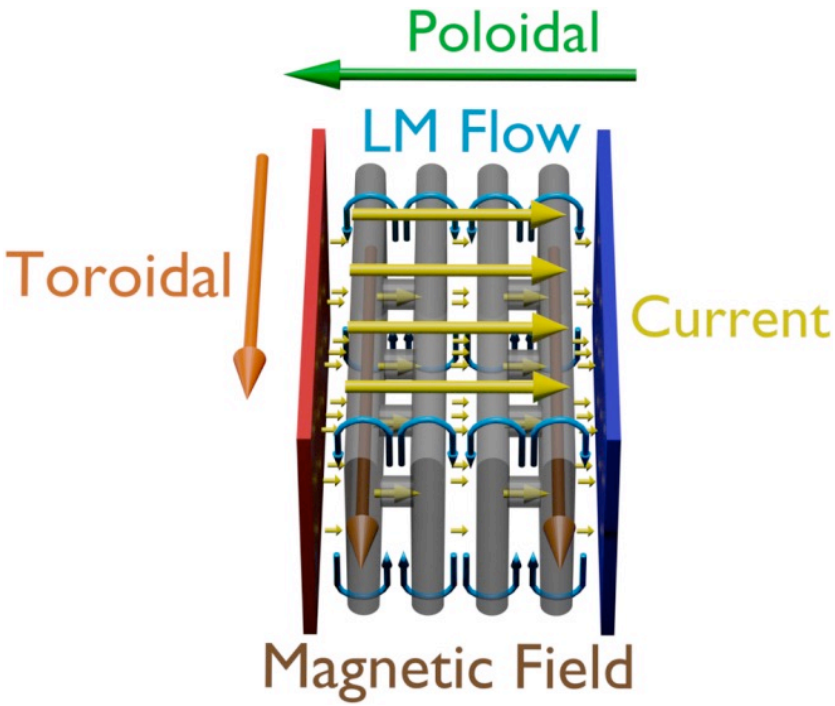


Saenz [NF, 2022]

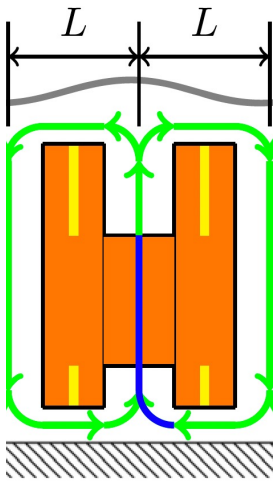


Operational principle of divertorlets

- 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 $\sim C_D \rho |\mathbf{U}|^2$



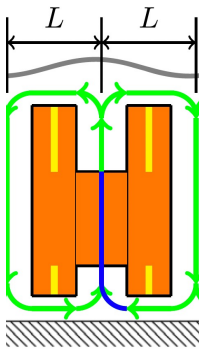
Fisher [NME, 2020]



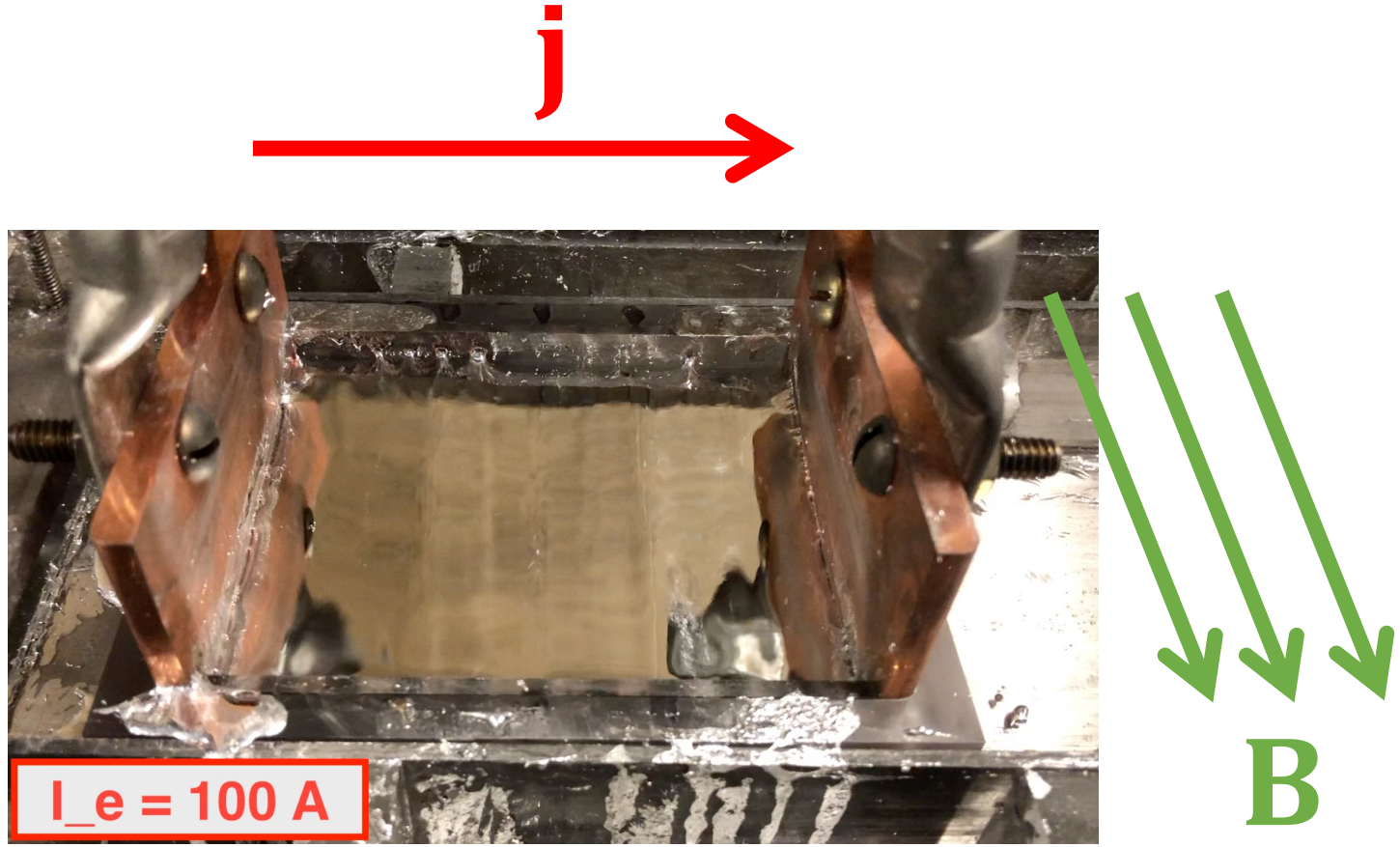
Saenz [NF, 2022]

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

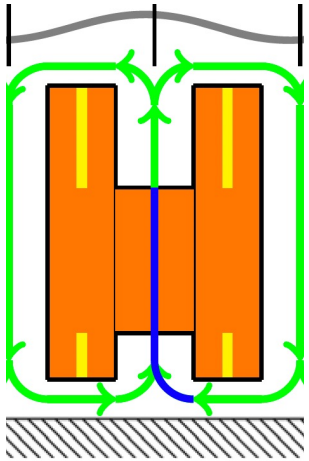


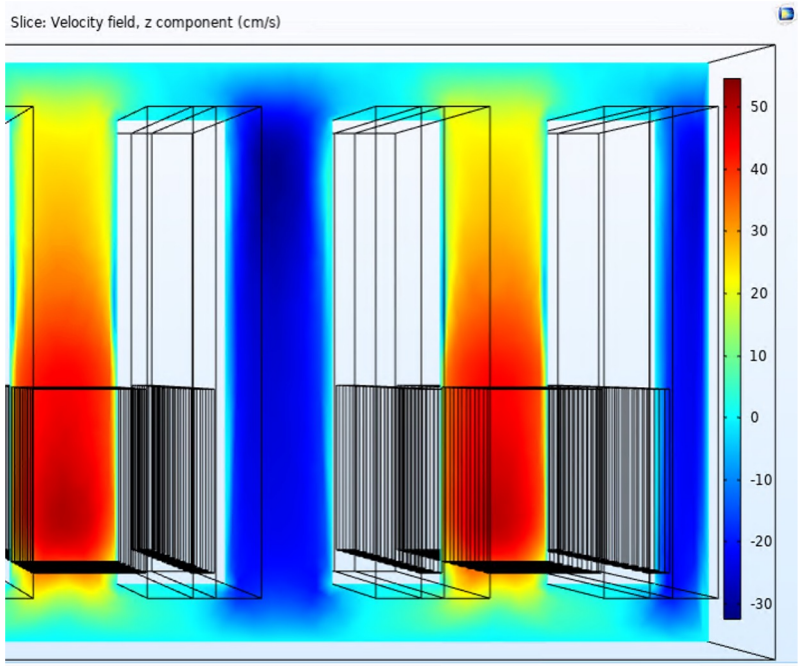
Saenz [NF, 2022]

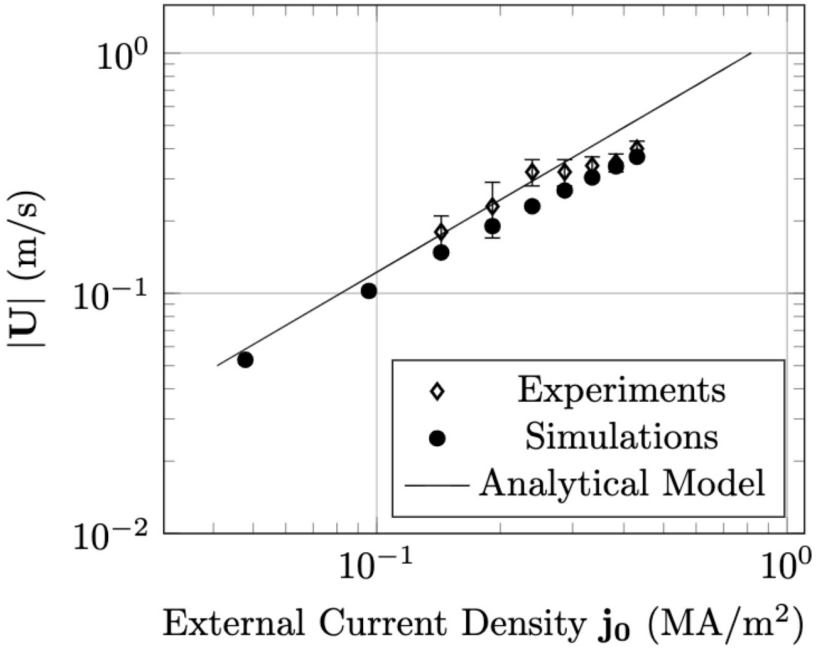


Simulations/Analytical review

- COMSOL simulations confirmed the desired flow loop around slats.
- Average upward velocities were compared to experimental results.
- Experiments and simulations were analytically reviewed.



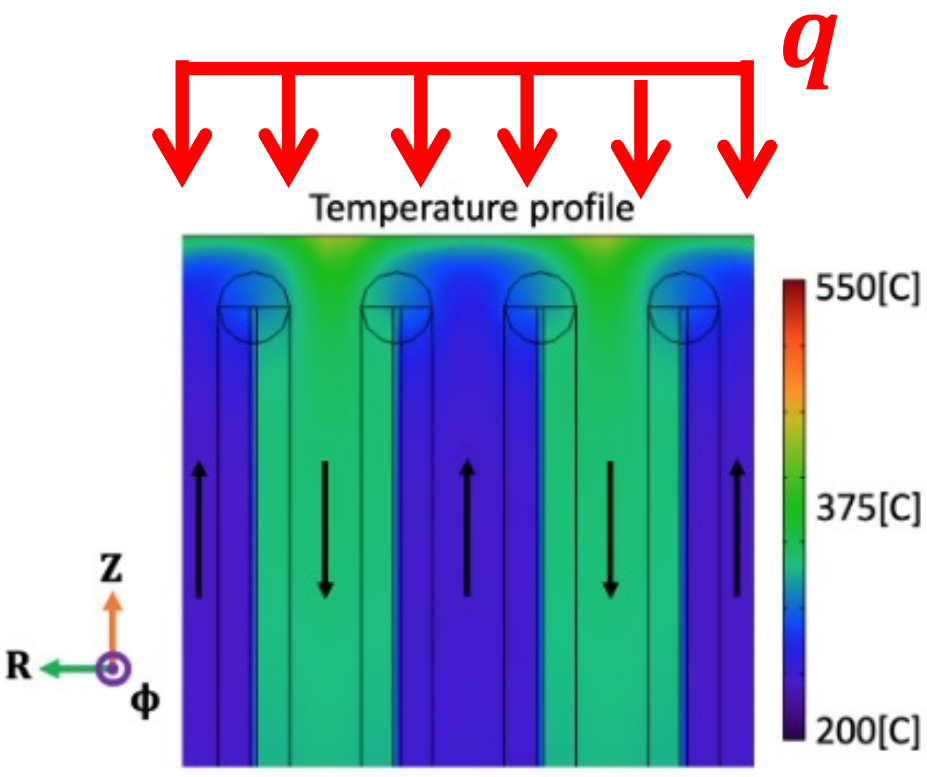




Saenz [NF, 2022]

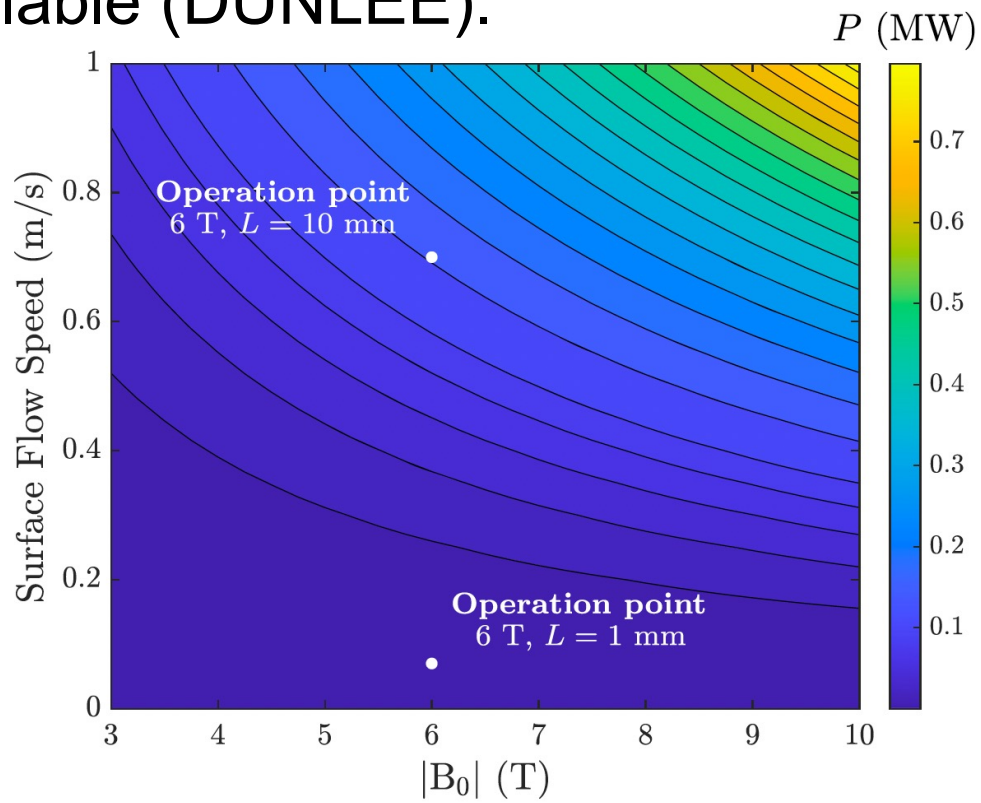
Projections at the reactor scale

- 10 MW/m^2 uniform heat load.
- Liquid lithium below 450˚C.



Fisher [NME, 2020]

- Less than 1% of power output of DEMO (500 MW).
- 100-micron tungsten 3D printing capability available (DUNLEE).



Saenz [NF, 2022]

Summary/future work

- Liquid metal flows encounter MHD drag when subject to magnetic fields, which generate piles of galinstan on free-surface flows.
- Simulations of free surface liquid metal flows are executed and in agreement with experimental results.
- The divertorlets concept is an alternative to fast-flow liquid metal concepts for divertor solutions.
- 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.
- Integration of cooling system for divertorlets/TEMHD analysis.

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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