PRINCETON UNIVERSITY

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Experimental, numerical and analytical evaluation Lorentz-force propulsion on liquid-metal channel flows for divertor applications at the NIFS Oroshhi-2 Facility

US-Japan and International Workshop on Power and Particle Control in DEMO Fusion Reactor by Liquid Metal Plasma-Facing Components

Francisco Saenz[1],

with A. Fisher[1], J. Al-Salami[2], T. Tanaka[3], T. Kunugi[4], J. Yagi[5], K. Kusumi[5], Y., Go[5], G. Yamazaki[6], B. Wynne[1], C. Hu[2], K. Hanada[2], E. Kolemen[7]

[1] Princeton University, USA
[2] Research Institute for Applied Mechanics, Kyushu University, Japan
[3] National Institute for Fusion Science, Japan
[4] Zhejiang University, P. R. China
[5] Kyoto University, Japan
[6] The Graduate University for Advanced Studies, SOKENDAI, Toki, Japan
[7] Princeton Plasma Physics Laboratory, USA

Plasma Control

Overview

- **Motivation**
  - Liquid metals for fusion applications.

- **Lorentz-force propulsion**

- **Experiments**
  - LMFREX/NIFS Oroshhi-2 Superconducting magnet facility.
  - Experimental setup.

- **Simulations**
  - Comparison with experiments
  - Projections

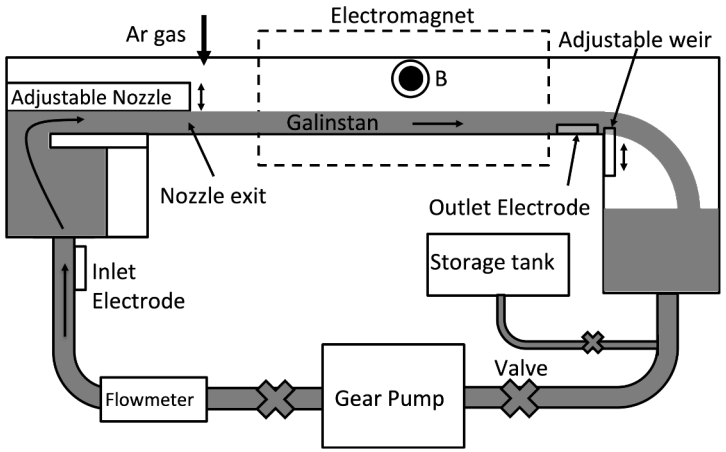
* Paper submitted to Nuclear Fusion Journal: "*Experimental, numerical and analytical evaluation of Lorentz-force propulsion for fast-liquid-metal-flow-divertor systems of nuclear fusion devices*". Article reference: NF-10599

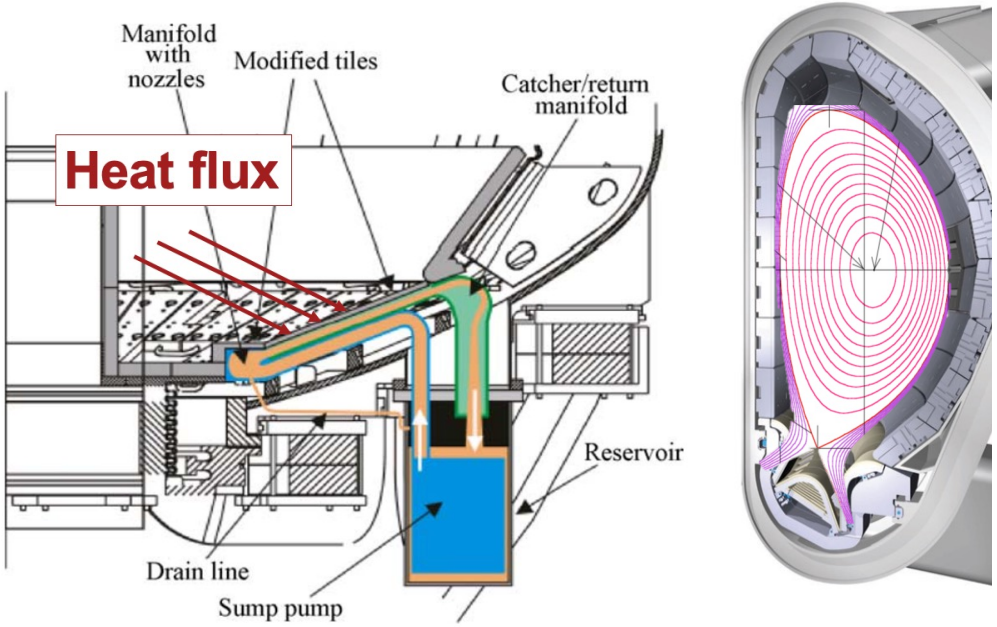
Plasma Control

Motivation

Liquid Metal R&D without plasmas.

- **Aim: To understand liquid metal flows at the small scale**
- New Divertor Ideas: j×B-forces to control of the LM flow and pumping.
- Non-evaporative liquid metal divertor for heat exhaust.



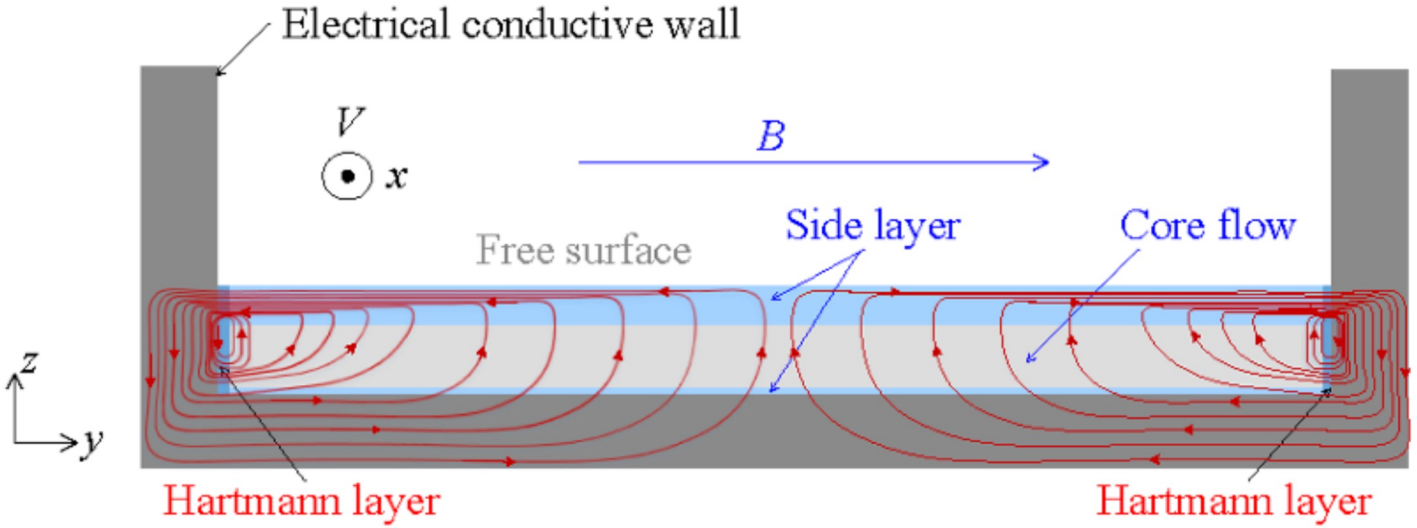


Heat flux on liquid metal divertor. Ying et al (2004)

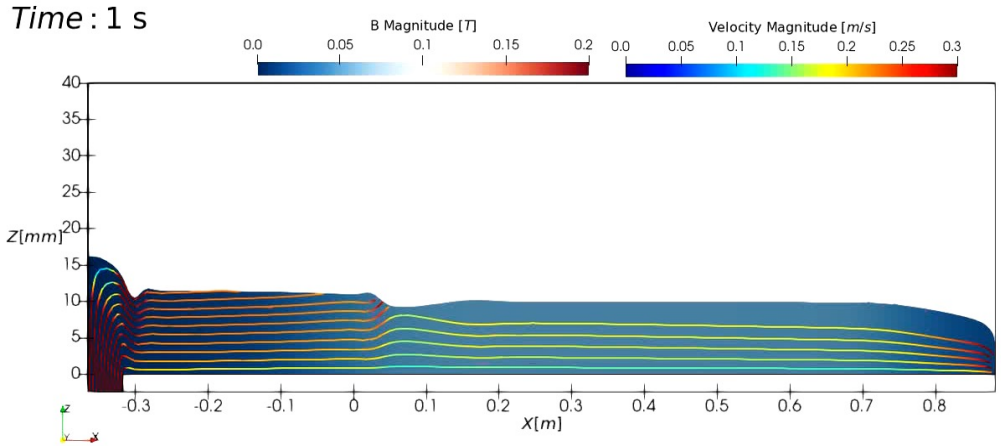
* A.Y. Ying, M.A. Abdou, N. Morley, T. Sketchley, R. Woolley, J. Burris, R. Kaita, P. Fogarty, H. Huang, X. Lao, M. Narula, S. Smolentsev, M. Ulrickson, Exploratory studies of flowing liquid metal divertor options for fusion-relevant magnetic fields in the MTOR facility, Fusion Engineering and Design, Volume 72, Issues 1–3, 2004, Pages 35-62, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2004.07.004.

MHD drag

- External magnetic field induce currents in liquid metals in motion.
- Induced currents cause a retarding force “MHD drag”.



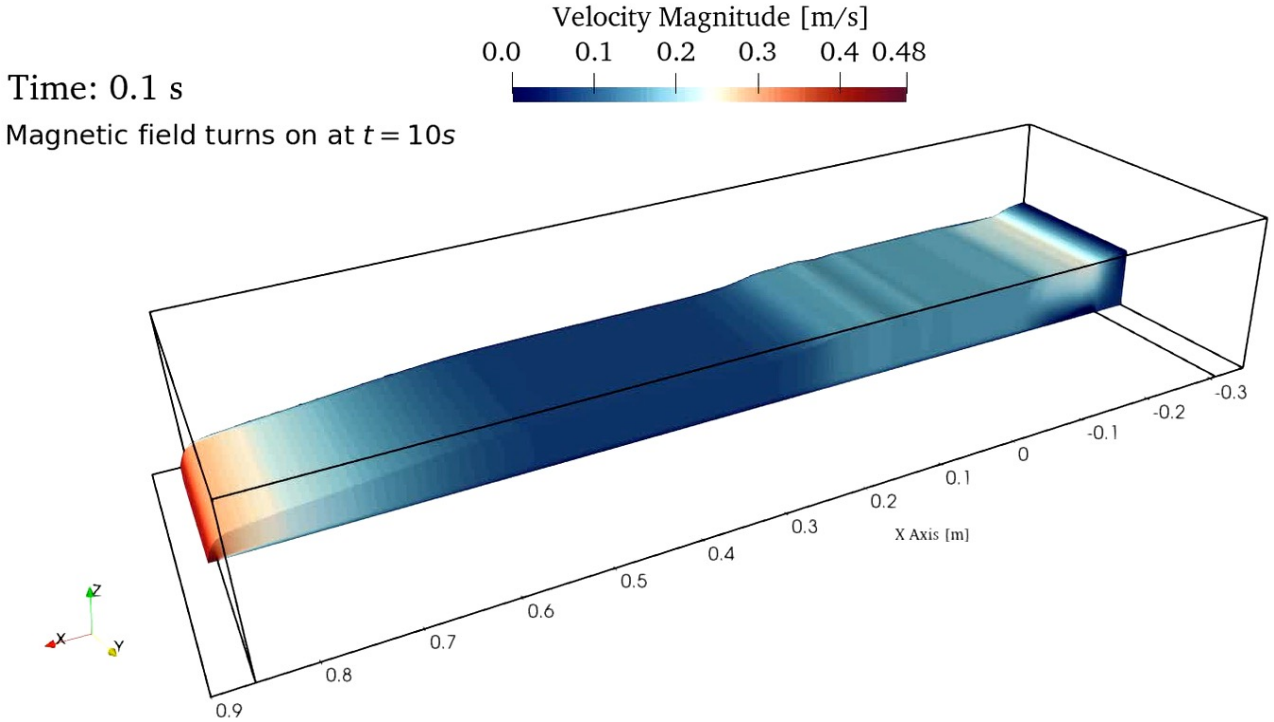
MHD induced current in a liquid metal. Yang et al (2020)*

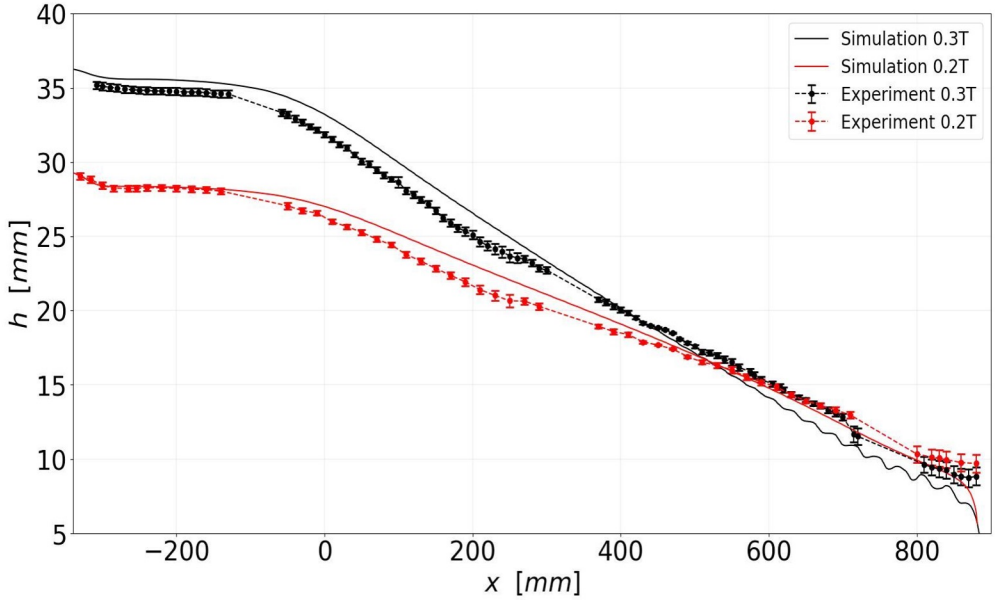


* Yang, J-C., T-Y. Qi, D-W. Ren, M-J. Ni, B-Q. Liu, J-S. Hu, and J-G. Li. "Magnetohydrodynamic effects on liquid metal film flowing along an inclined plate relating to plasma facing components." Nuclear Fusion 60, no. 8 (2020): 086003.

Code validation

- Experiments in LMX-U with different conditions that affect MHD drag forces.
- 3D Liquid Metal Magnetohydrodynamics (3DLMM)
- MHD drag ~ flow speed × $|\mathbf{B}|^2$

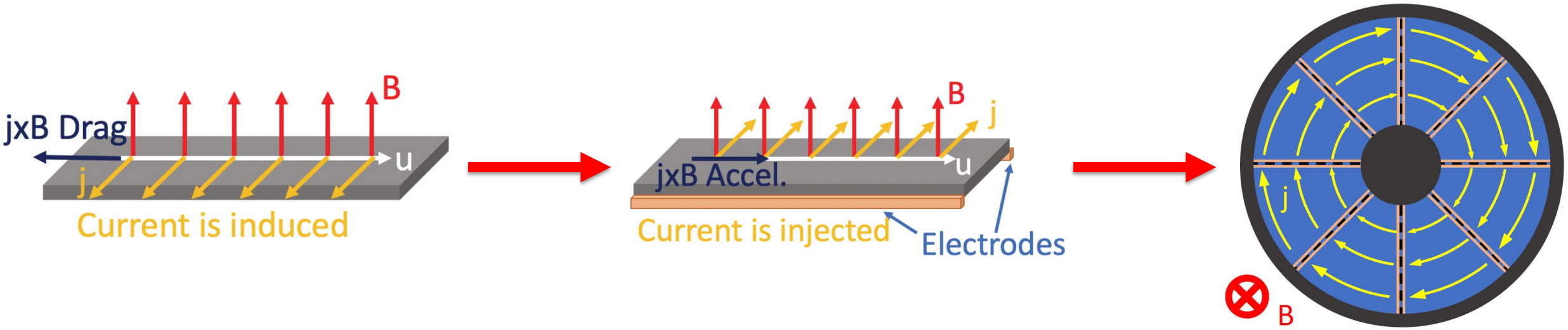




* Sun, Z., Al-Salami, J., Khodak, A., Saenz, F., Wynne, F., Maingi, R., Hanada, K., Kamra, K., Hu, C., & Kolemen, E. *Magnetohydrodynamics in free surface liquid metal flow relevant to plasma facing components*.

Lorentz-force propulsion

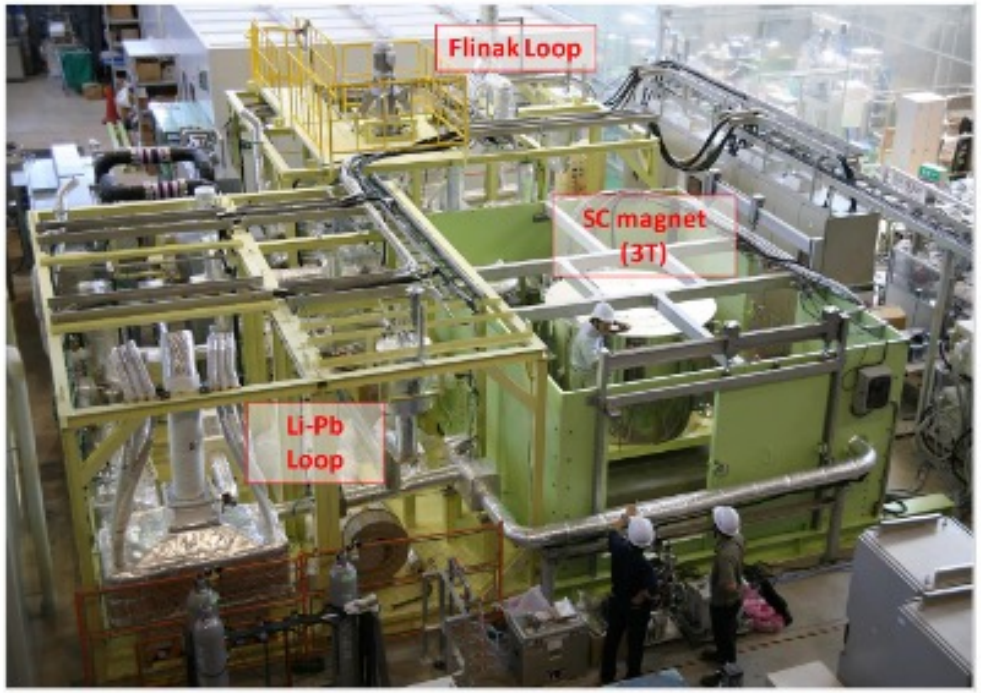
Lorentz-force propulsion



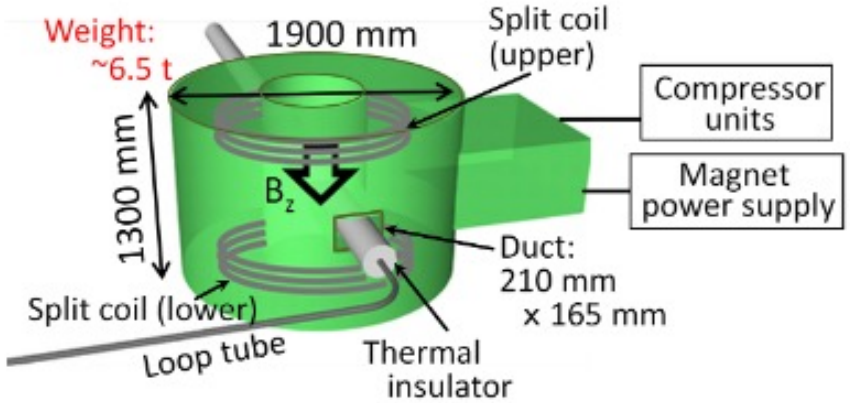
NIFS Oroshhi-2 Superconducting magnet

For our experiments:

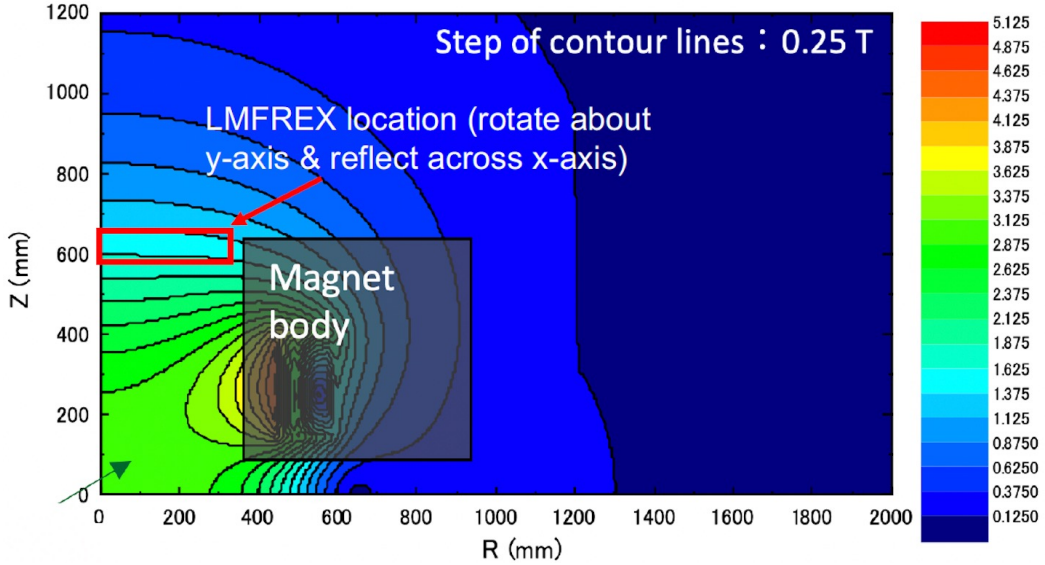
- Maximum Bz is ~1.4 T.
- Bz variation is ~5%



The bird's-eye view of Oroshhi-2. Sagara et al (2015)*



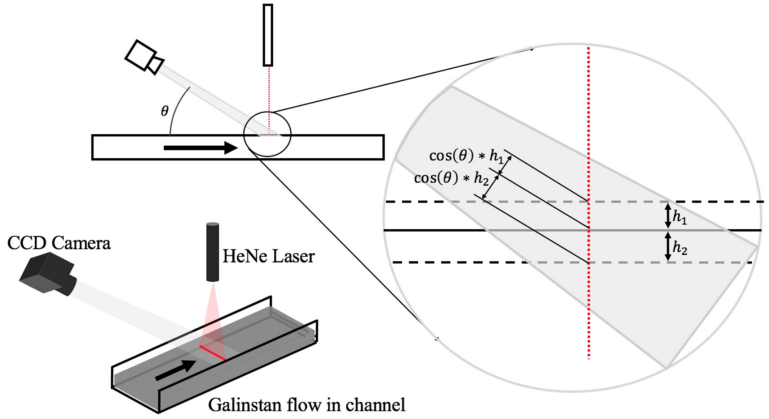
Dimensions of 3T magnet and area of uniform magnetic field. Sagara et al (2015)*

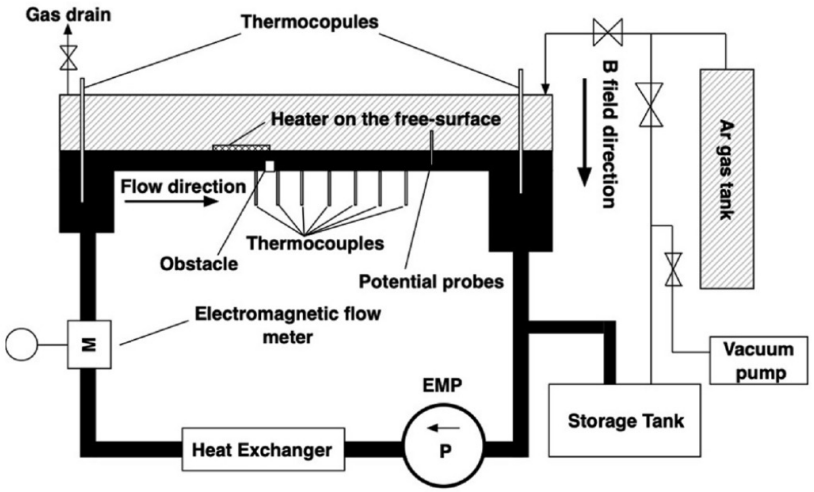


* Akio Sagara, Teruya Tanaka, Juro Yagi, Mitsutoshi Takahashi, Kuniaki Miura, Takehiko Yokomine, Satoshi Fukada & Shintaro Ishiyama (2015) First Operation of the Flinak/LiPb Twin Loop Orosh2i-2 with a 3T SC Magnet for R&D of Liquid Blanket for Fusion Reactor, Fusion Science and Technology, 68:2, 303-307, DOI: 10.13182/FST15-126

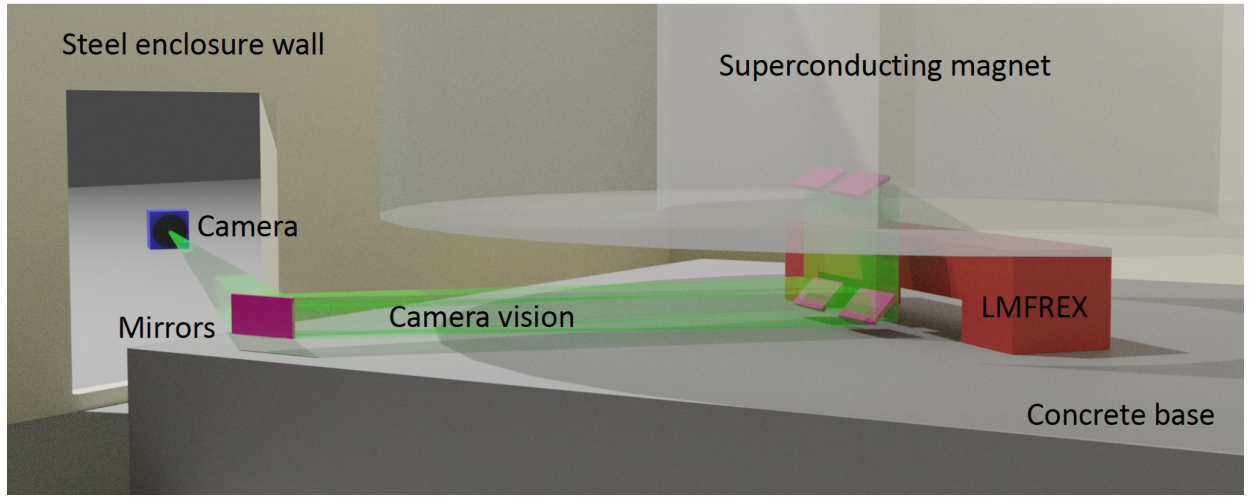
LMFREX Channel

- Galinstan (GaInSn alloy).
  - Electrical conductivity: 3.1 MS/m, (Li: 3.43 MS/m).



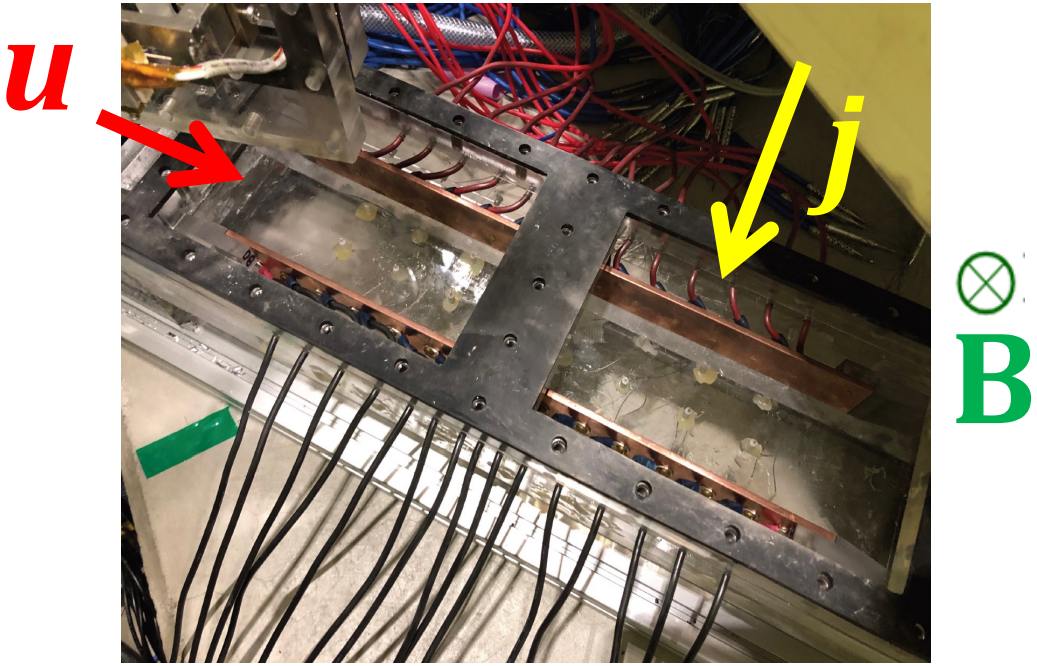


Schematic view of experimental apparatus of LMFREX (black area is GaInSn; shaded area is argon gas). Kusumi et al (2019)*

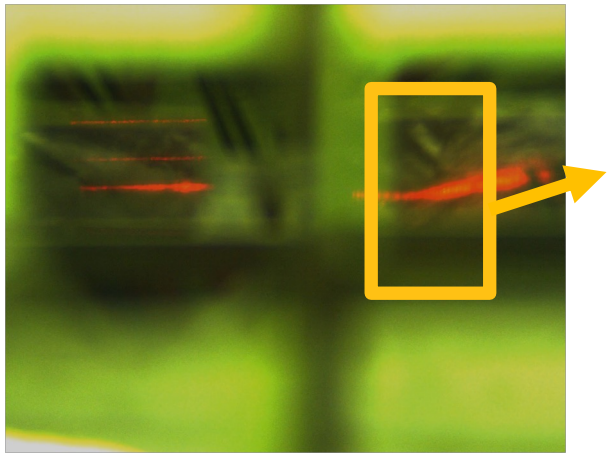


* Koji Kusumi, Tomoaki Kunugi, Takehiko Yokomine, Zensaku Kawara, Yuchen Wu, Akio Sagara, Teruya Tanaka, Thermal mixing enhancement of liquid metal film-flow by various obstacles under vertical magnetic field, Fusion Engineering and Design, Volume 146, Part B, 2019, Pages 2158-2162, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2019.03.128

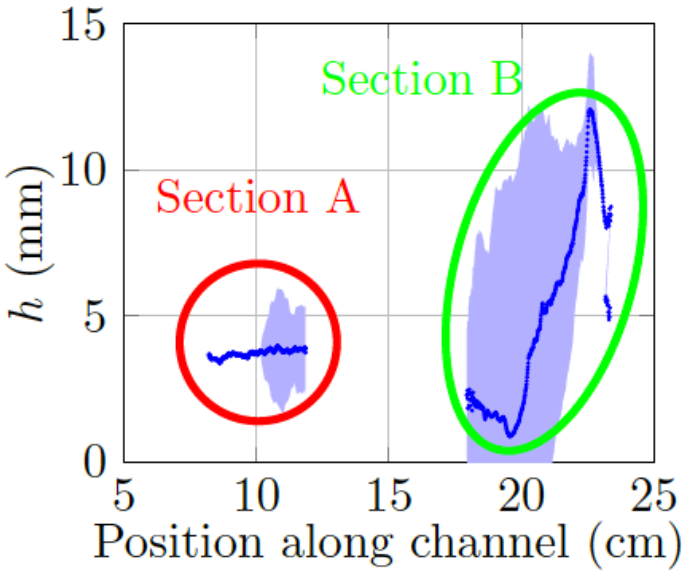
Experimental setup



120 A, 0.1 T

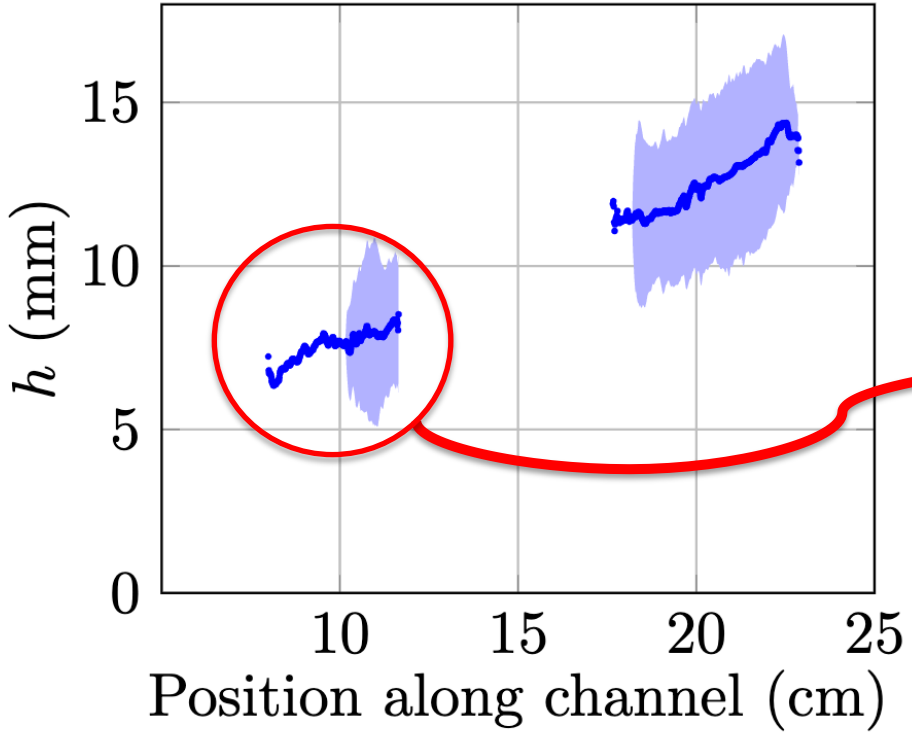


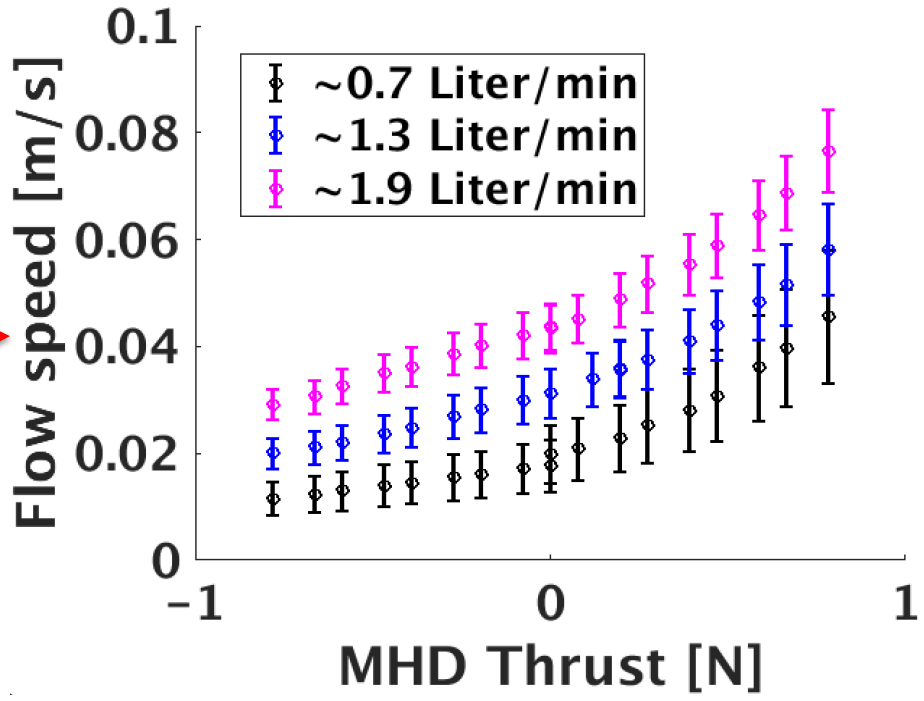
Jump-like discontinuity!



Experimental Results: j×B thrust

60 A, 0.1 T



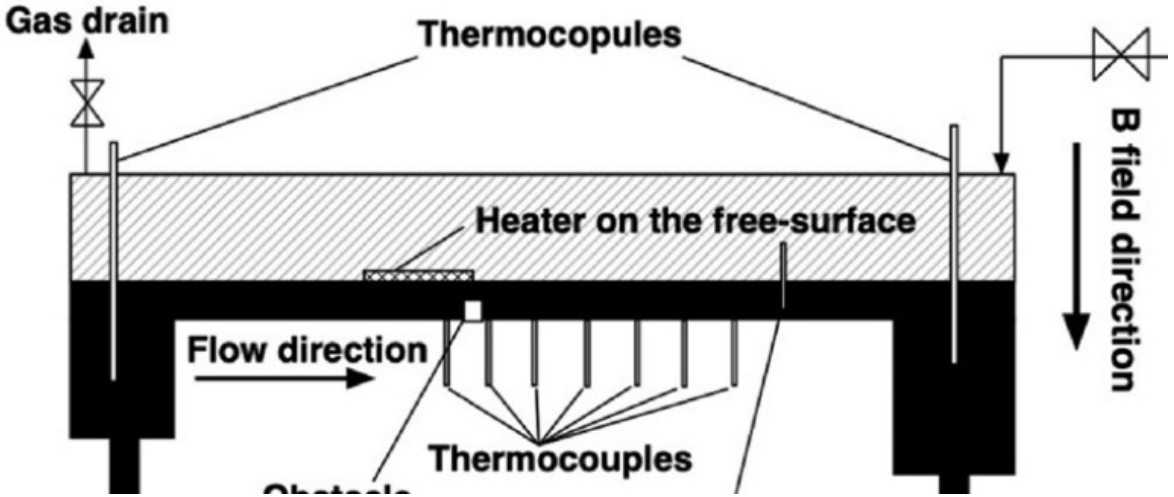


Some observations during experiments

- Sensitivity to initial infill level of liquid metal:
  - Excessive thrust leaves an empty channel.
  - Flow detachment from walls.
  - Basin at the outlet causes accumulation.

Flow detached!

8 A, 1.02 T



Plasma Control

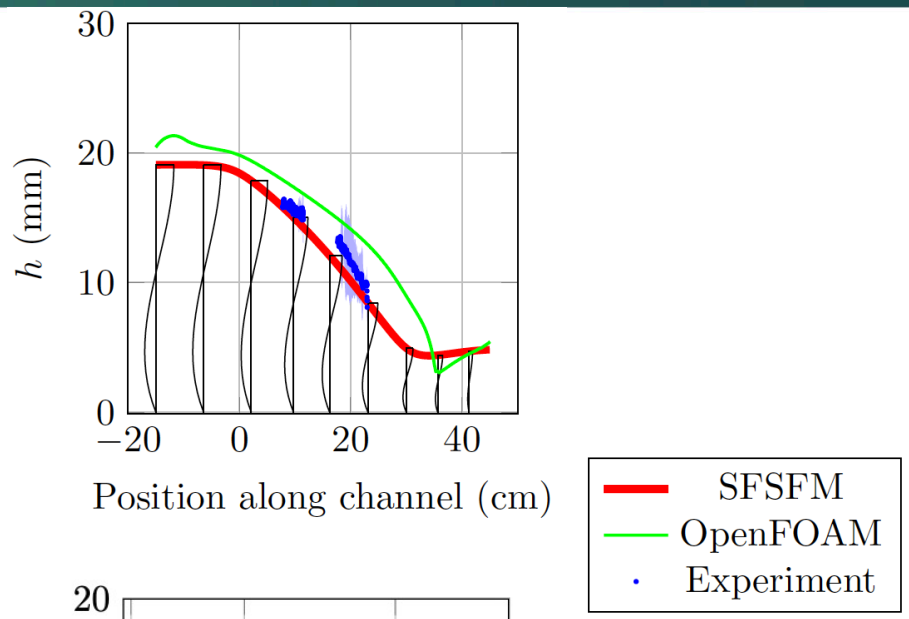
Simulations

Validation of 3DLMM

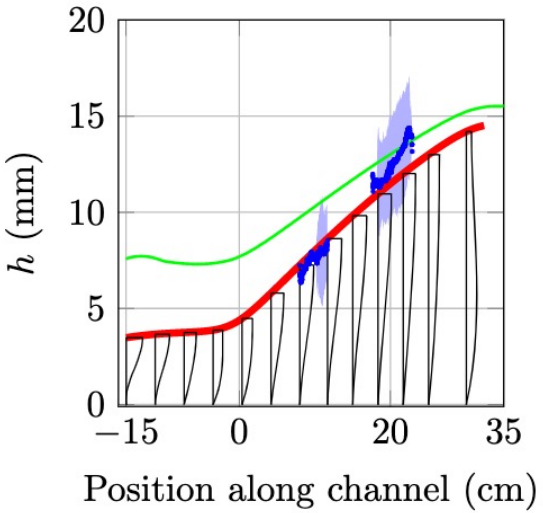
- Validation of simulation code with experiments.
- Theoretical solutions with Shallow-Free-Surface-Flow model (SFSFM).

$$\left.\begin{aligned} \frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} &= 0 \\ \rho(\mathbf{U}\cdot\nabla)u &= -\frac{\partial p}{\partial x} + (\mathbf{j}\times\mathbf{B})_x + \mu\nabla^2 u \end{aligned}\right\}$$

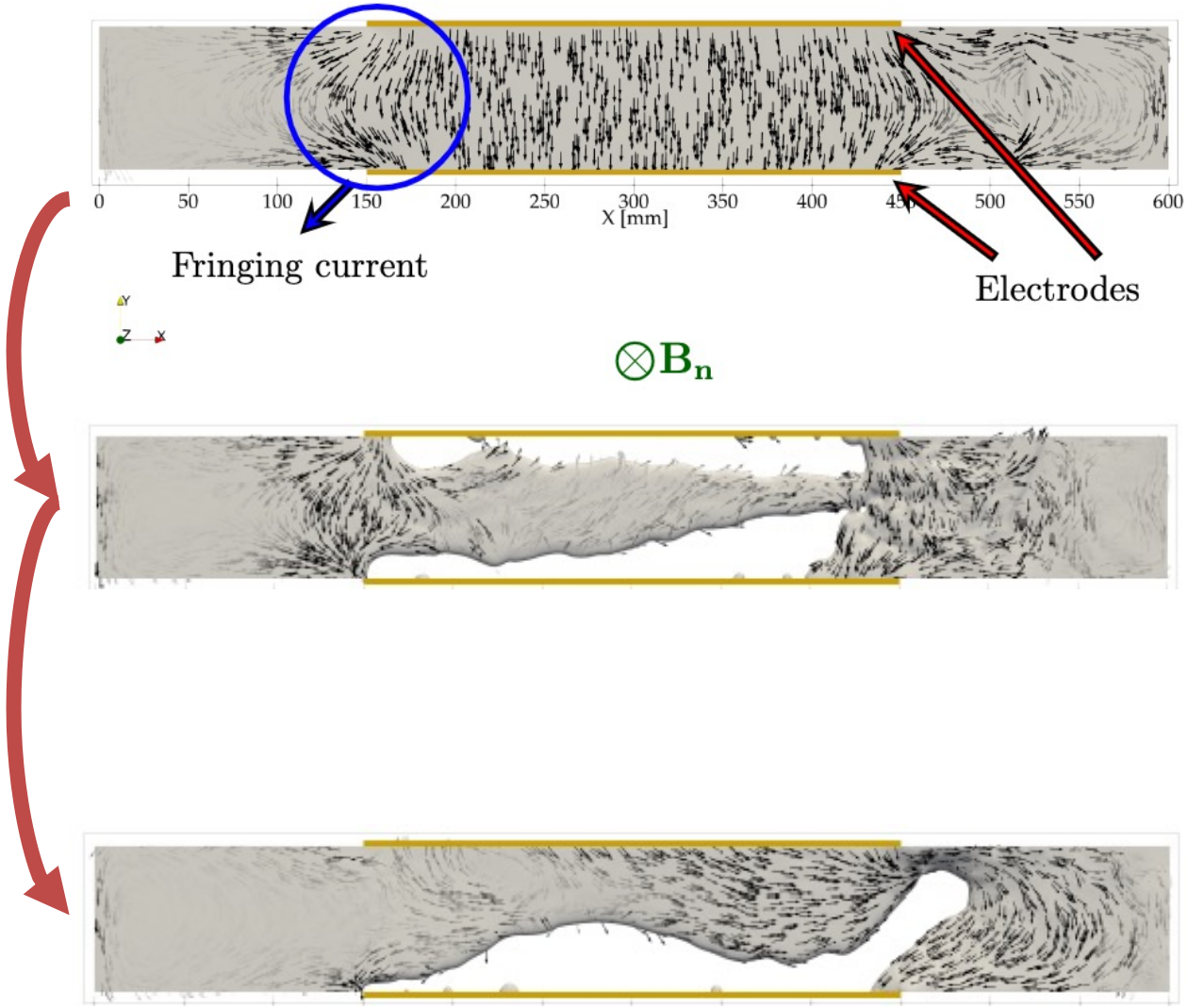
Q = 0.7 L/min
I = -20 A
B = 0.61 T



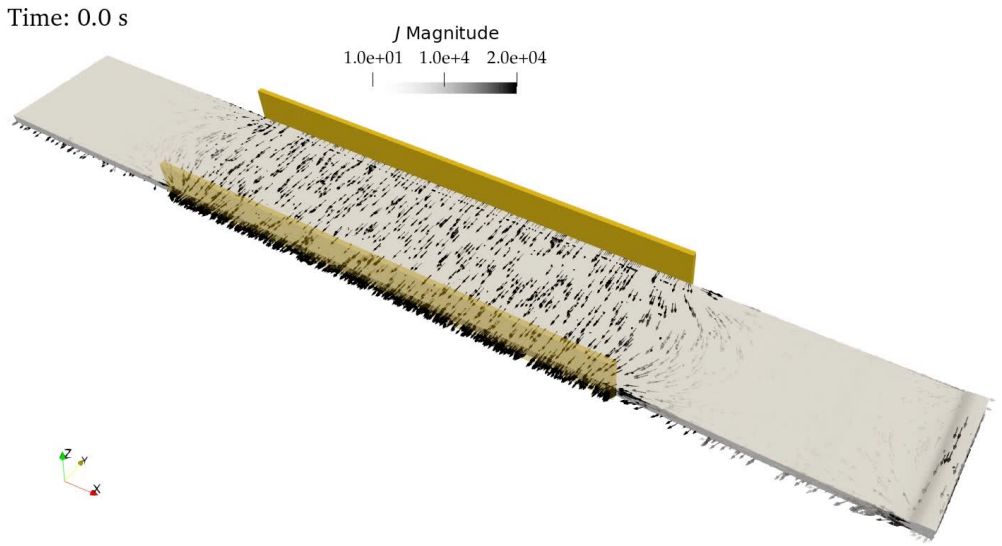
Q = 1.9 L/min
I = 60 A
B = 0.103 T



Fringing currents



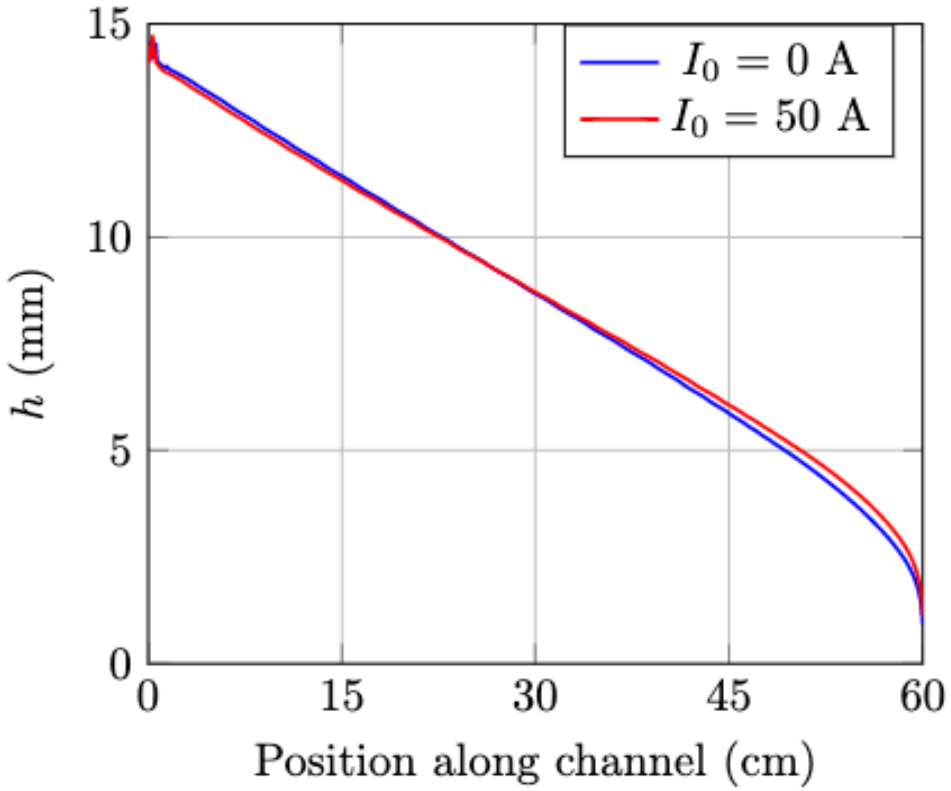
- Q = 1.9 L/min, I0 = 60 A, B = 0.103 T



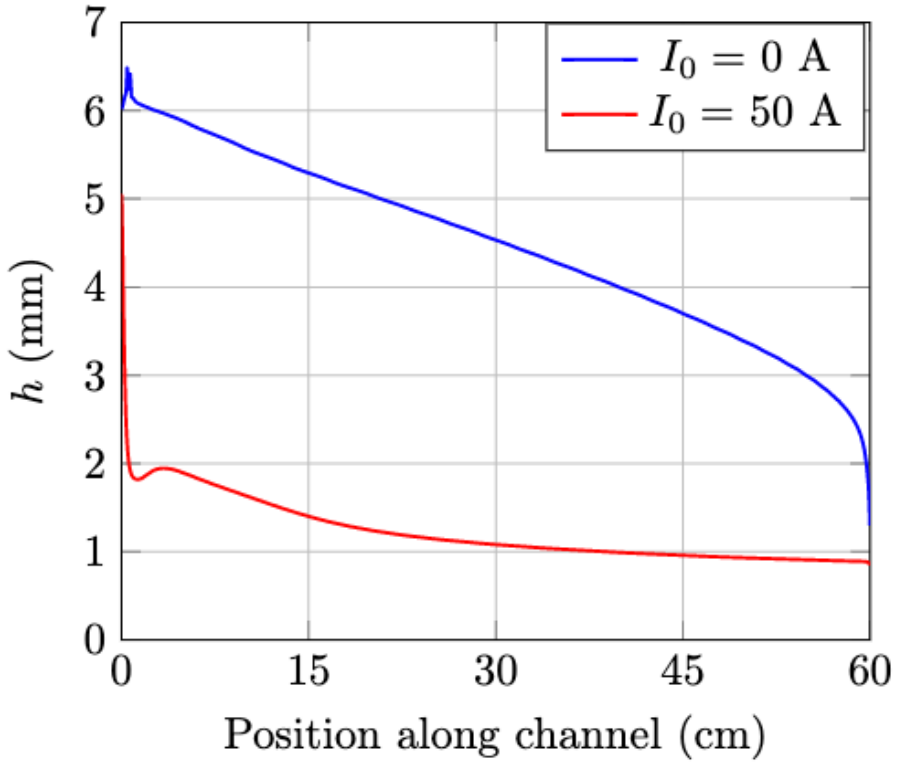
Effects of substrate conductivity

- $|B_n| = 1$ T, liquid lithium, Q = 10 L/min, $t_w = 2.5$ mm
  - Electrodes as long as channel to eliminate fringing currents.

Tungsten



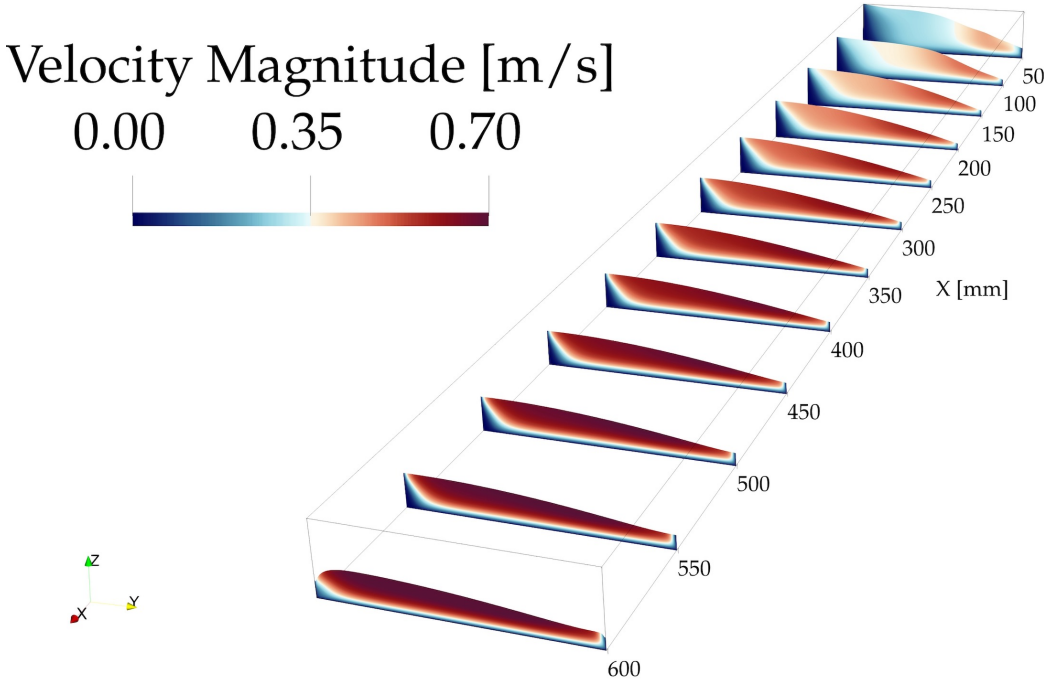
Insulated



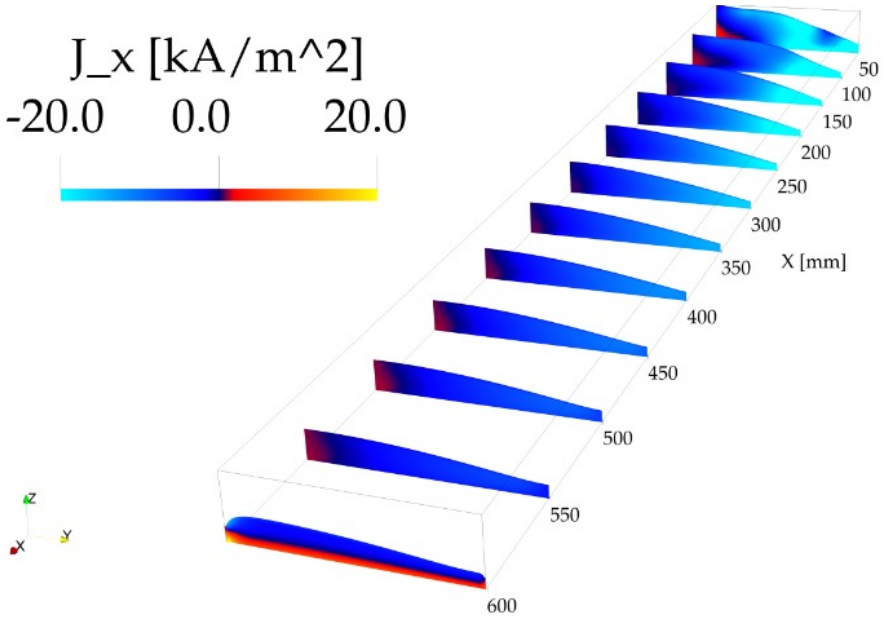
Velocity gradients

- $|B_n| = 1$ T, liquid lithium, Q = 10 L/min.
  - Insulated substrate.

- **Developing flow**



- **Axial currents**



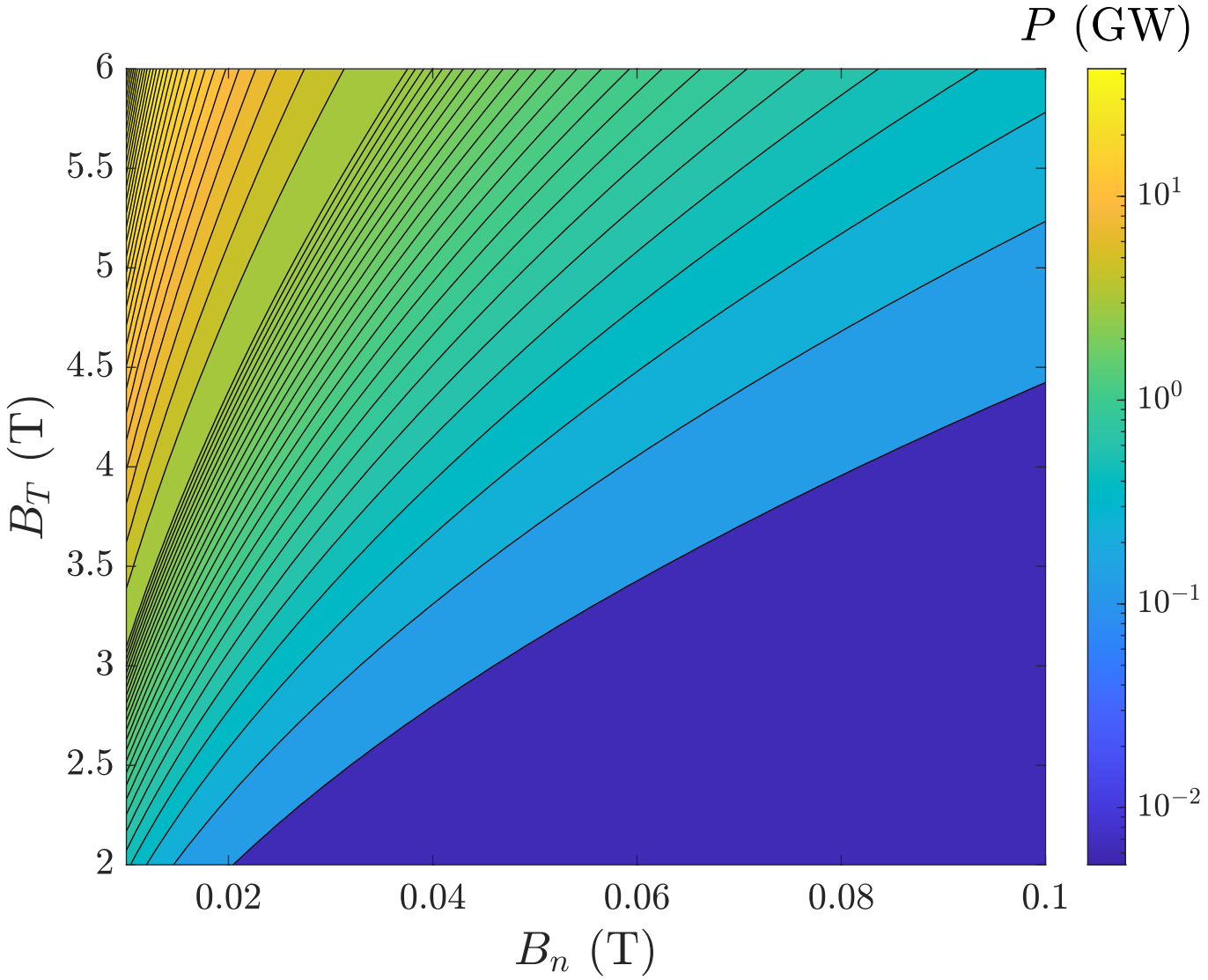
(d) Stream-wise currents for $I_0 = 50$ A. h is increased by a factor of 10.

Projections for 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 ~ 10 cm
  - Liquid metal thickness ~ 1 cm
  - Flow speed to avoid evaporation

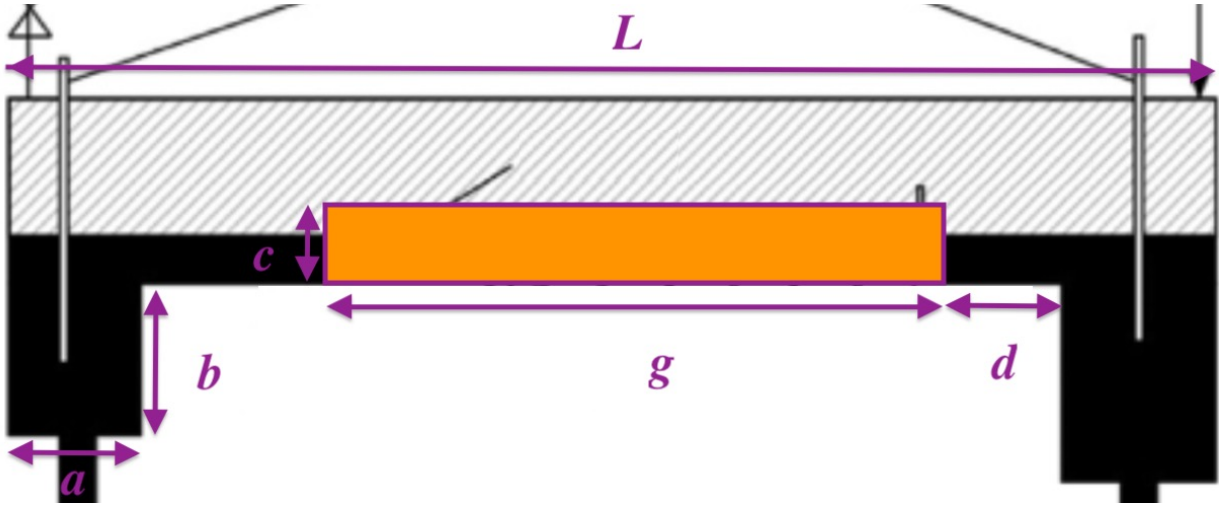


Summary

- 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.
- Simulations of free surface liquid metal flows were executed and in agreement with experimental results.
- Power requirements are excessive for Lorentz-force propulsion, far from being attractive for fusion devices.

Thanks for your attention!

Backup


L
c
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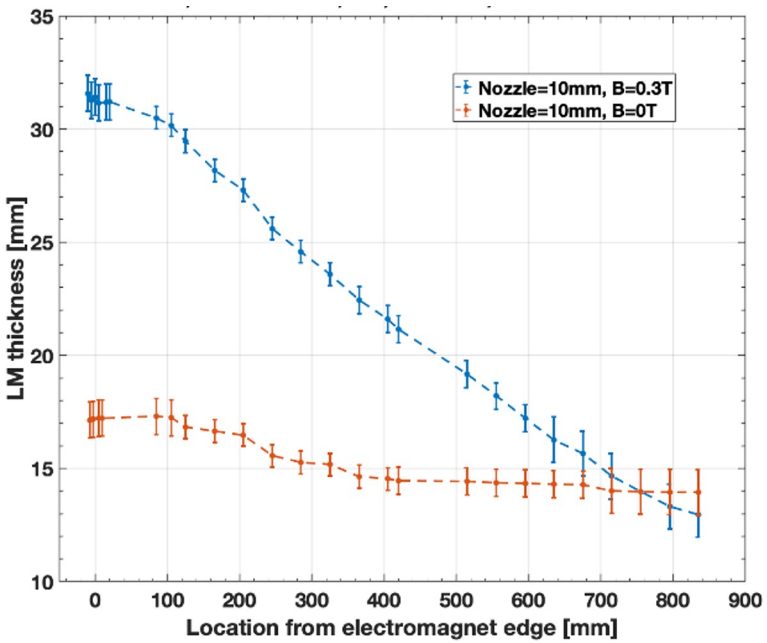
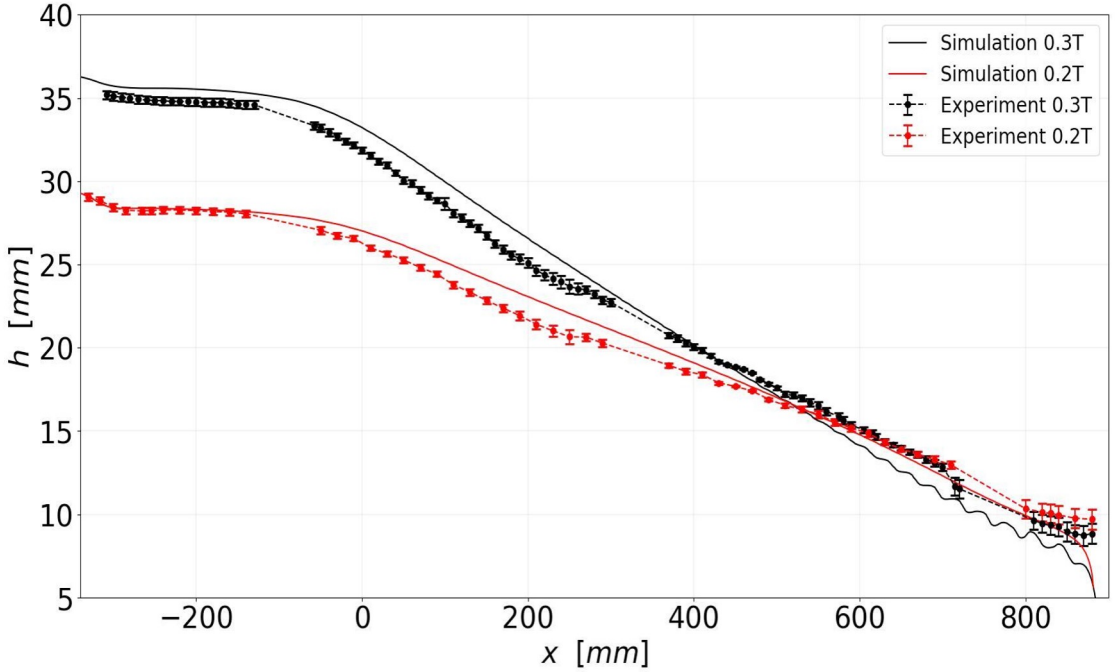
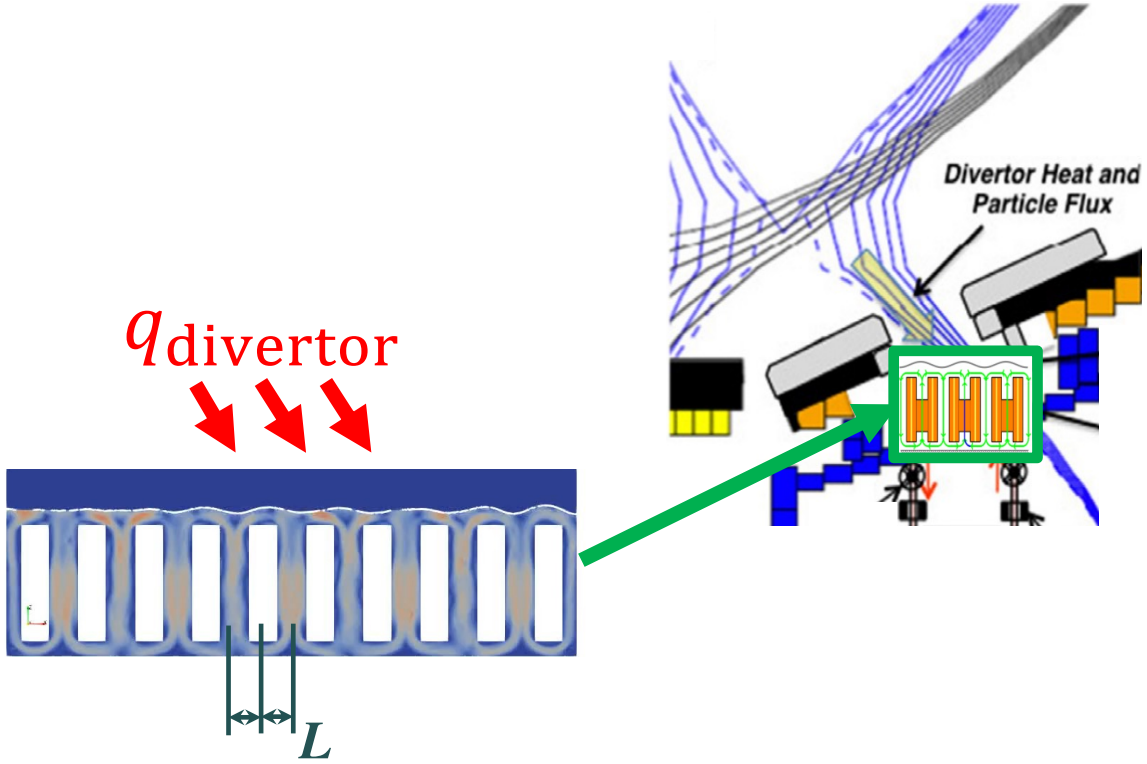
MHD Drag experiments

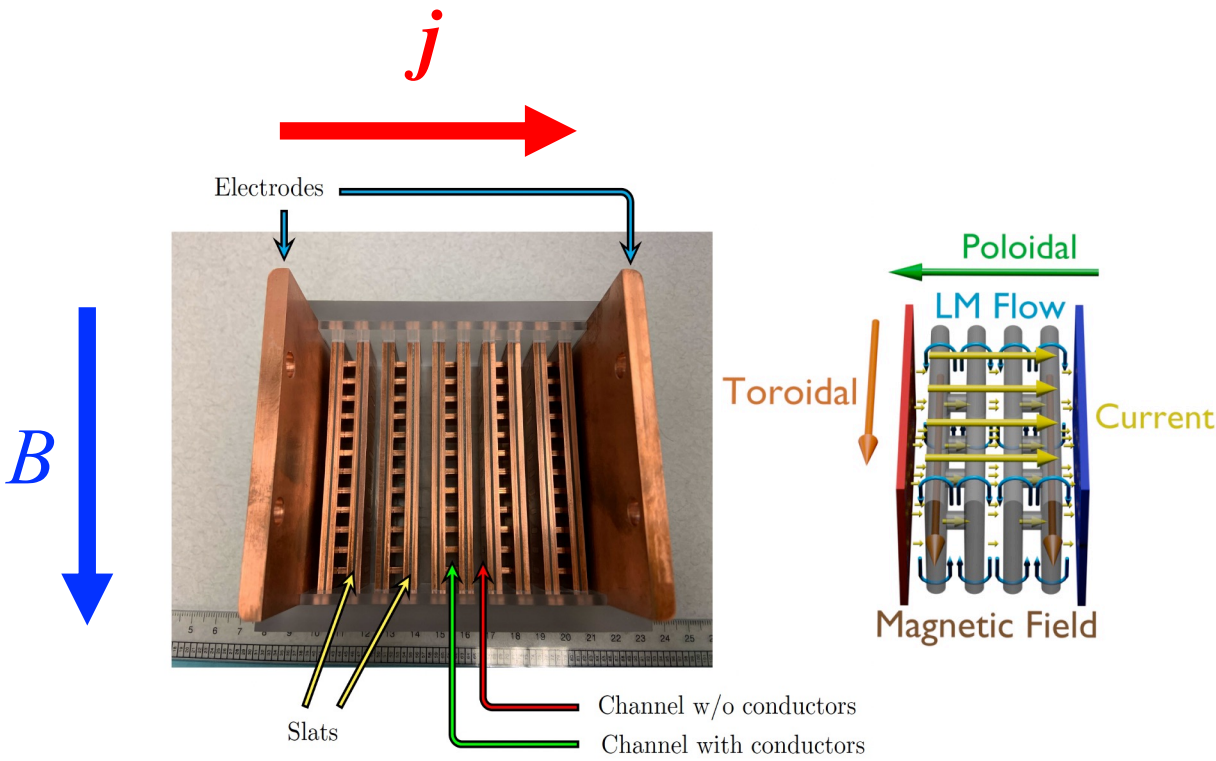
- 3D Liquid Metal Magnetohydrodynamics (3DLMM)





Divertorlets



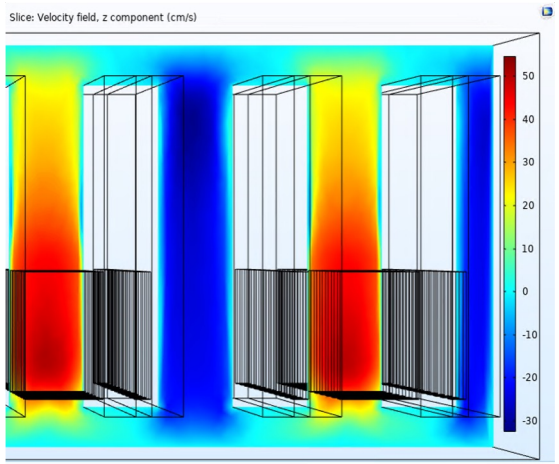


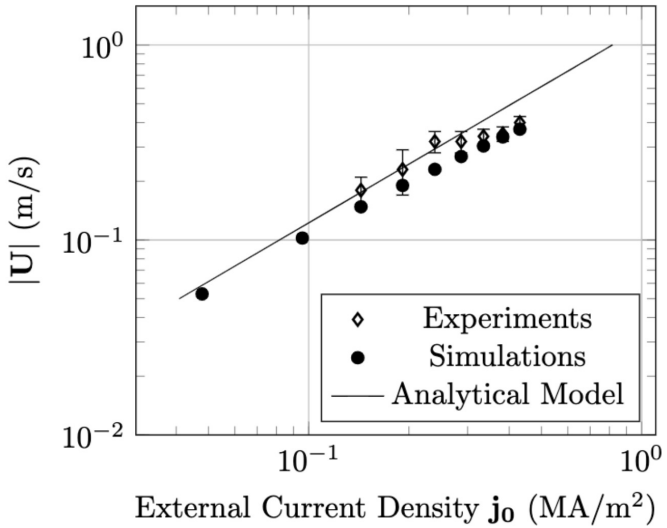
Top view

Divertorlets

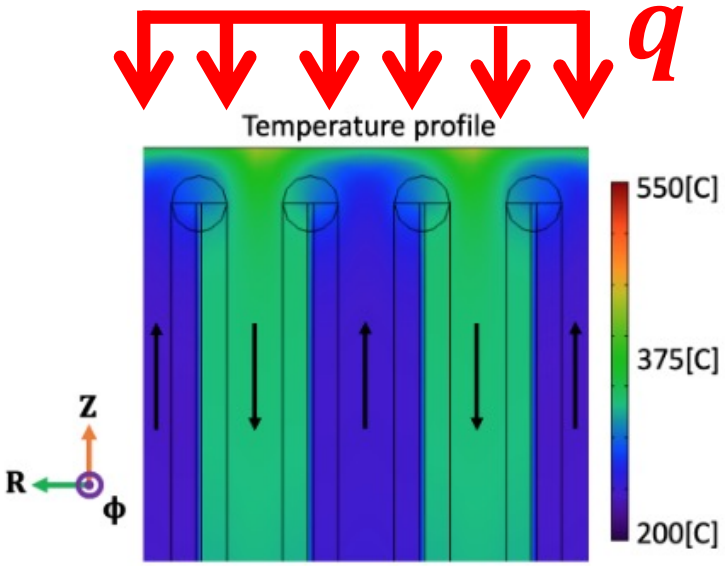
Simulations/Analytical review/Projections

- Simulations confirmed the desired flow loop around slats.

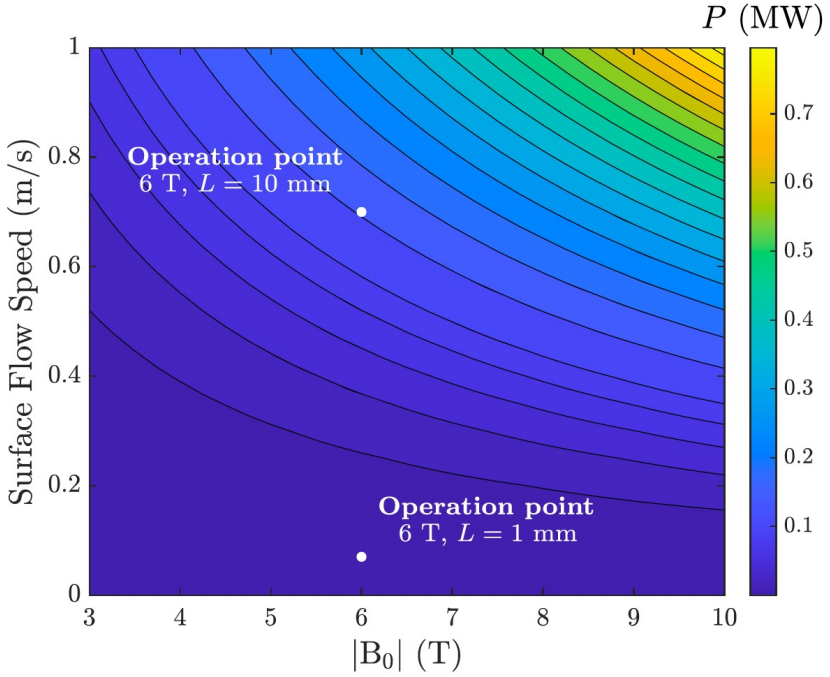




- 10 MW/m^2 uniform heat load.
- Liquid lithium below 450˚C.



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



Plasma Control

Projections at the reactor scale