Fast Flowing Liquid Metal Divertor Options: Experimental and Numerical Studies

Egemen Kolemen

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PRINCETON UNIVERSITY

Mechanical & Aerospace Engineering

Jointly appointed with the Andlinger Center for Energy and the Environment and the Plasma Physics Laboratory (PPPL)

PPPL PRINCETON PLASMA PHYSICS LABORATORY

andlinger center for energy+the environment

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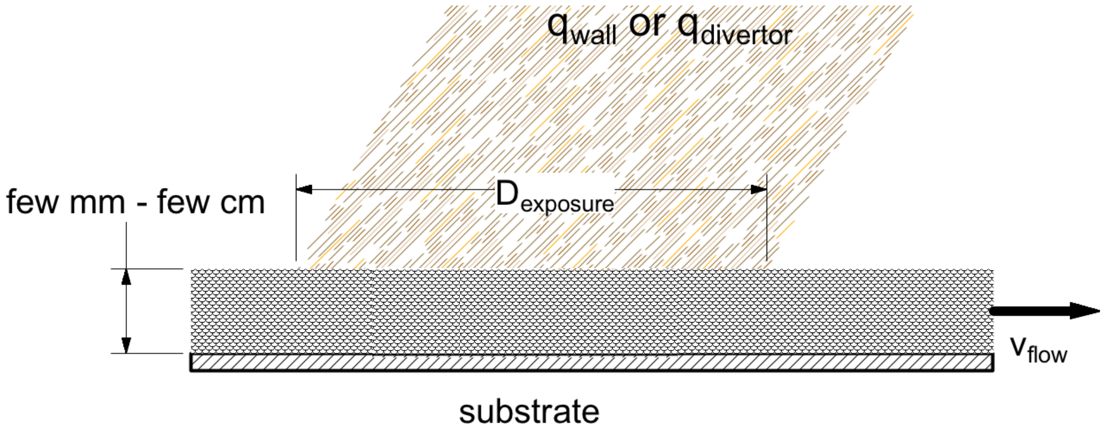
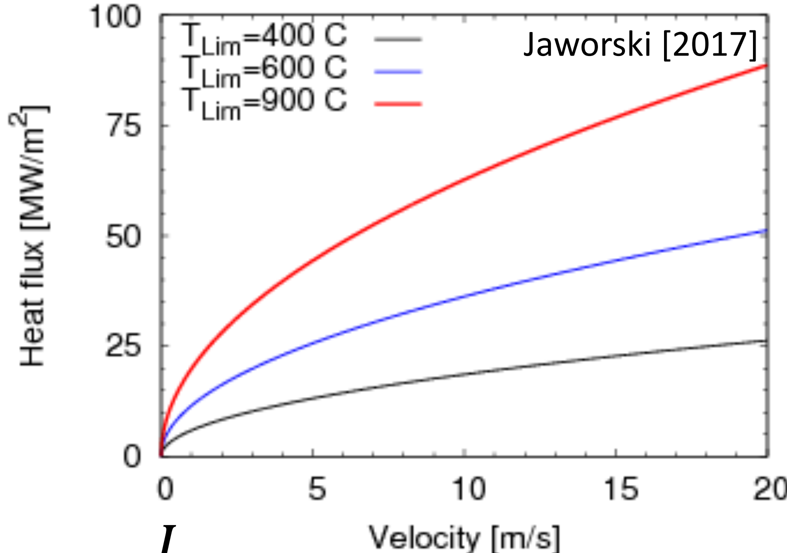
IAEA Divertor Workshop
Vienna, Austria

Nov, 2019

Fast Liquid Metal (LM) Flow Divertor Can Remove All The Divertor Heat Flux





$$t_{cr} = (\Delta T / 2q)^2 \pi k \rho c_p \, , \qquad v = \frac{L}{t_{rc}}$$

- ***Non-evaporative*** **LM divertor requires fast flow ~1-20 m/s**
- **Fast LM for surface protection and heat removal**
- **No material issues, but need to flow fast to take all the heat!**
- **The solid substrate behind only needs to handle neutrons (no cooling system)**
- **LM can also pump D/T and possibly He**
- **Simplifies the design for compact reactor**

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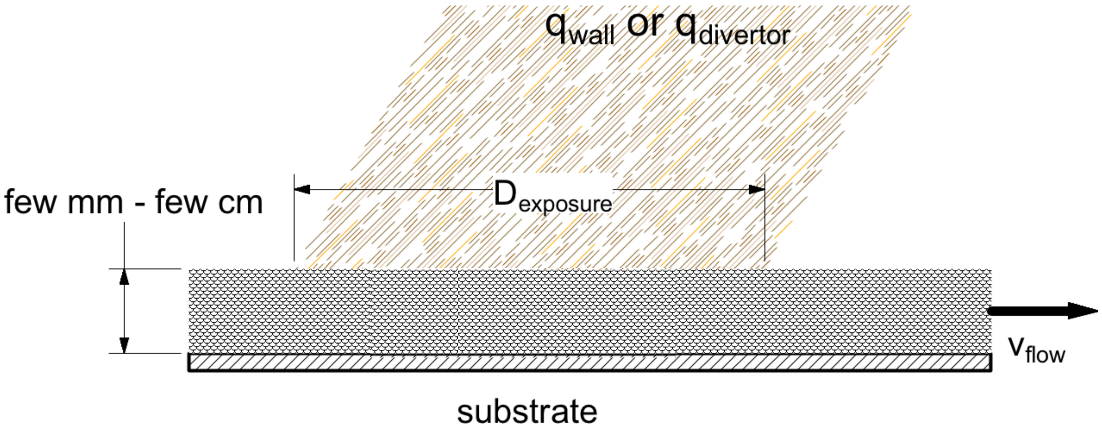

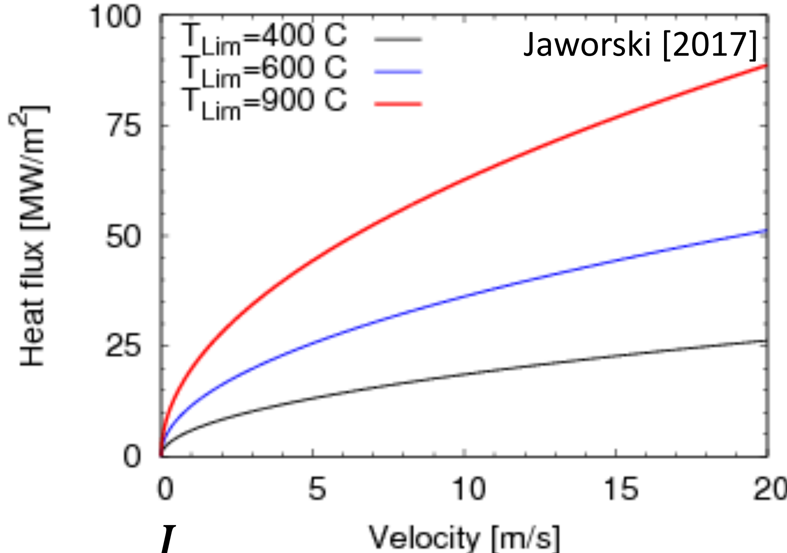

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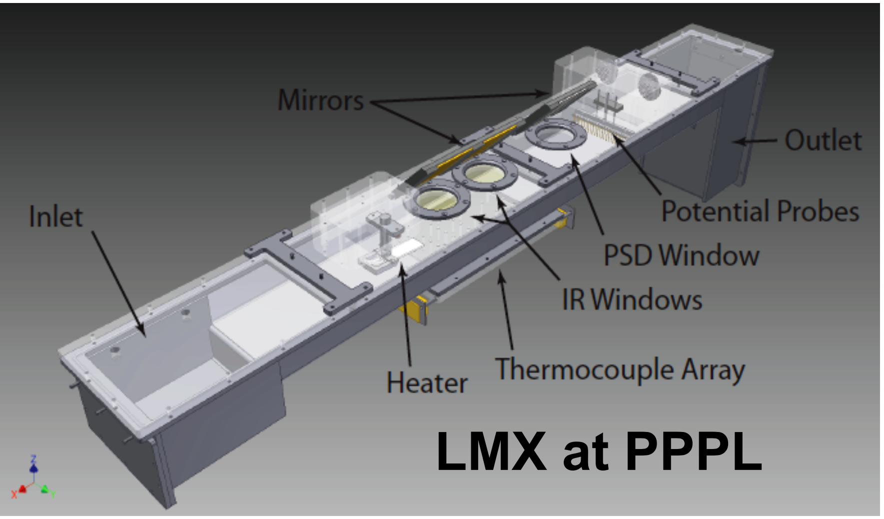
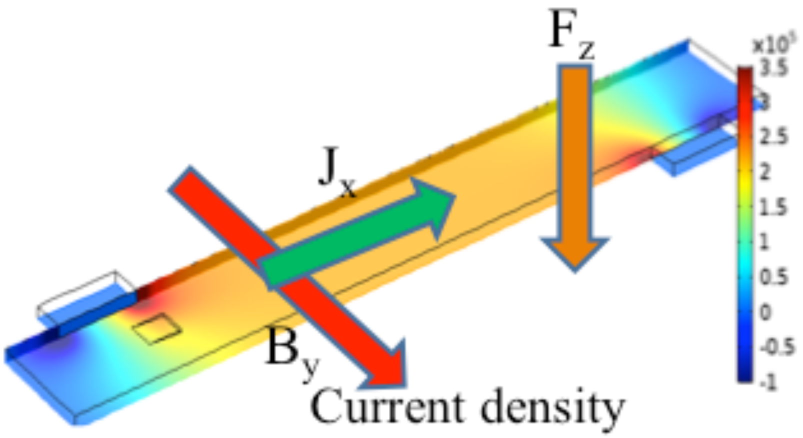
Main Results: Velocity Control, Heat Transport Enhancement and Flow Stabilization in Fast Liquid Metal (LM) Flows

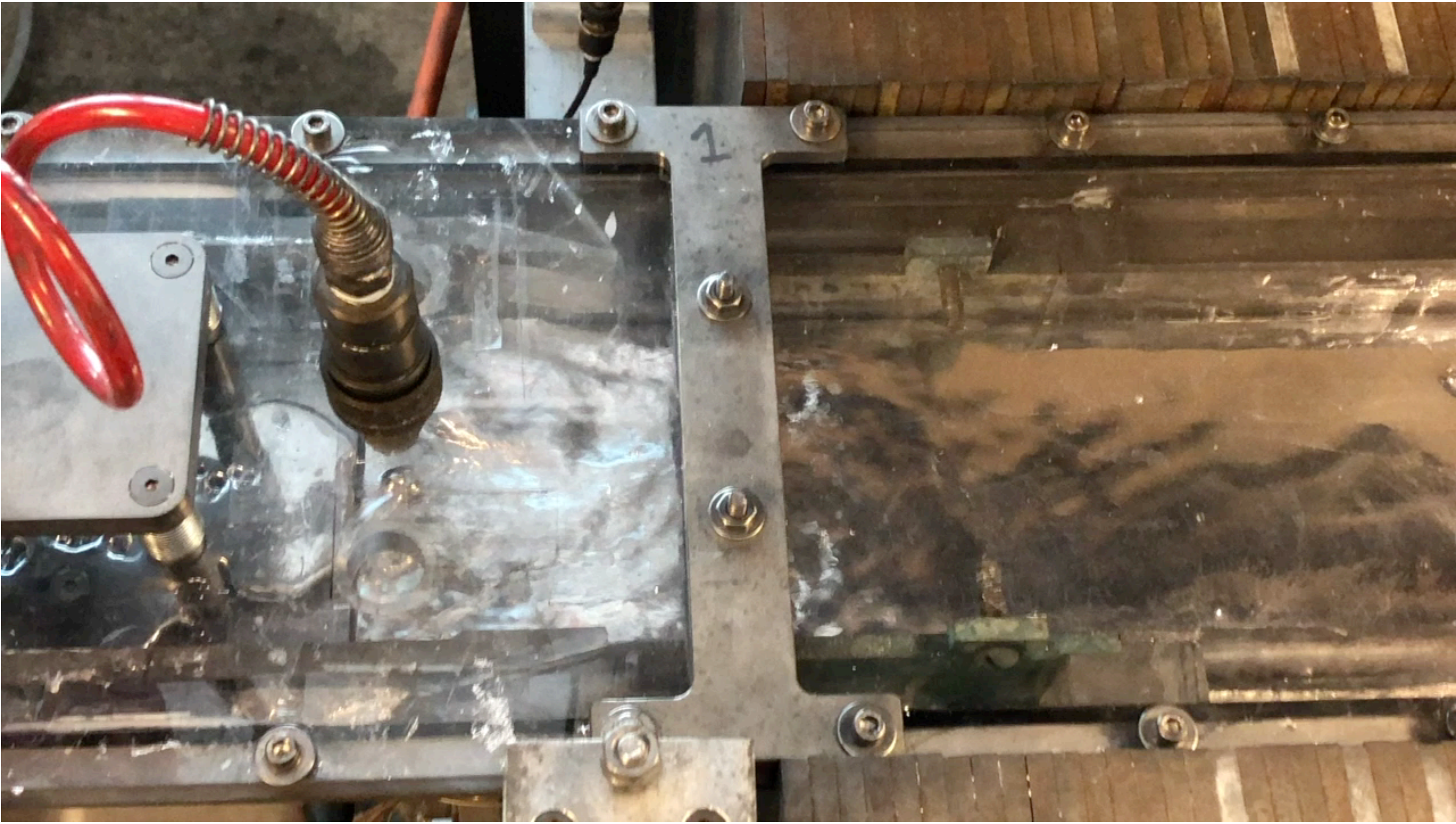




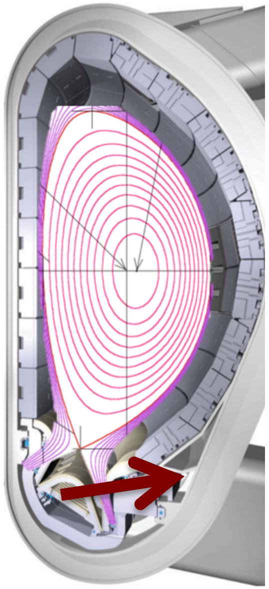
- **Using various techniques at Liquid Metal eXperiment (LMX) and Orosshi-2 (Japan), we showed**

1. **Control of flow velocity and height**
2. **Flow stabilization against hydraulic jumps**
3. **Enhance Heat Transport from top to the bottom of the LM**

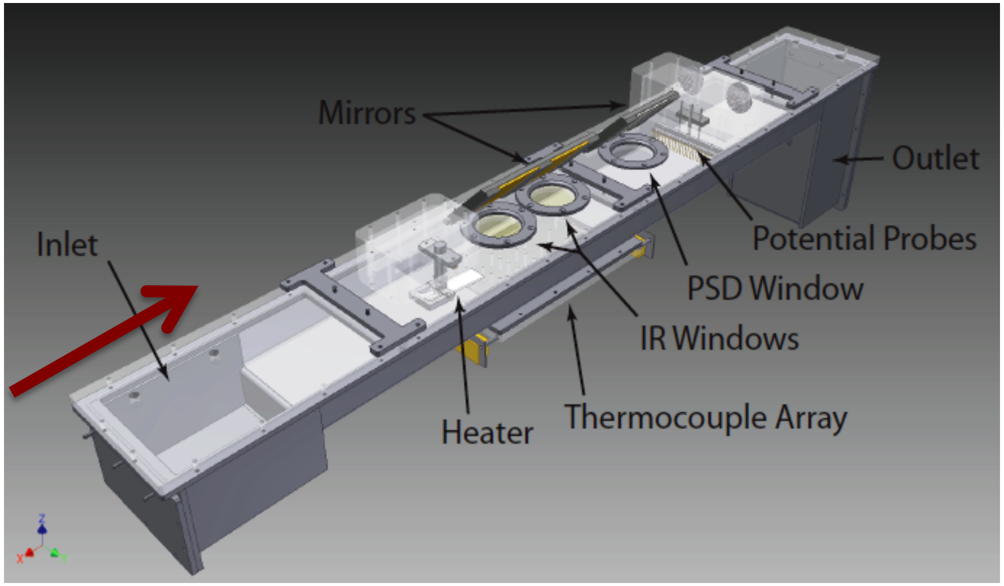
Introduction/Orientation:
Fast Free Surface LM Flow in a Channel (LMX)



Flowing Liquid Metal R&D without Plasma



Tokamak



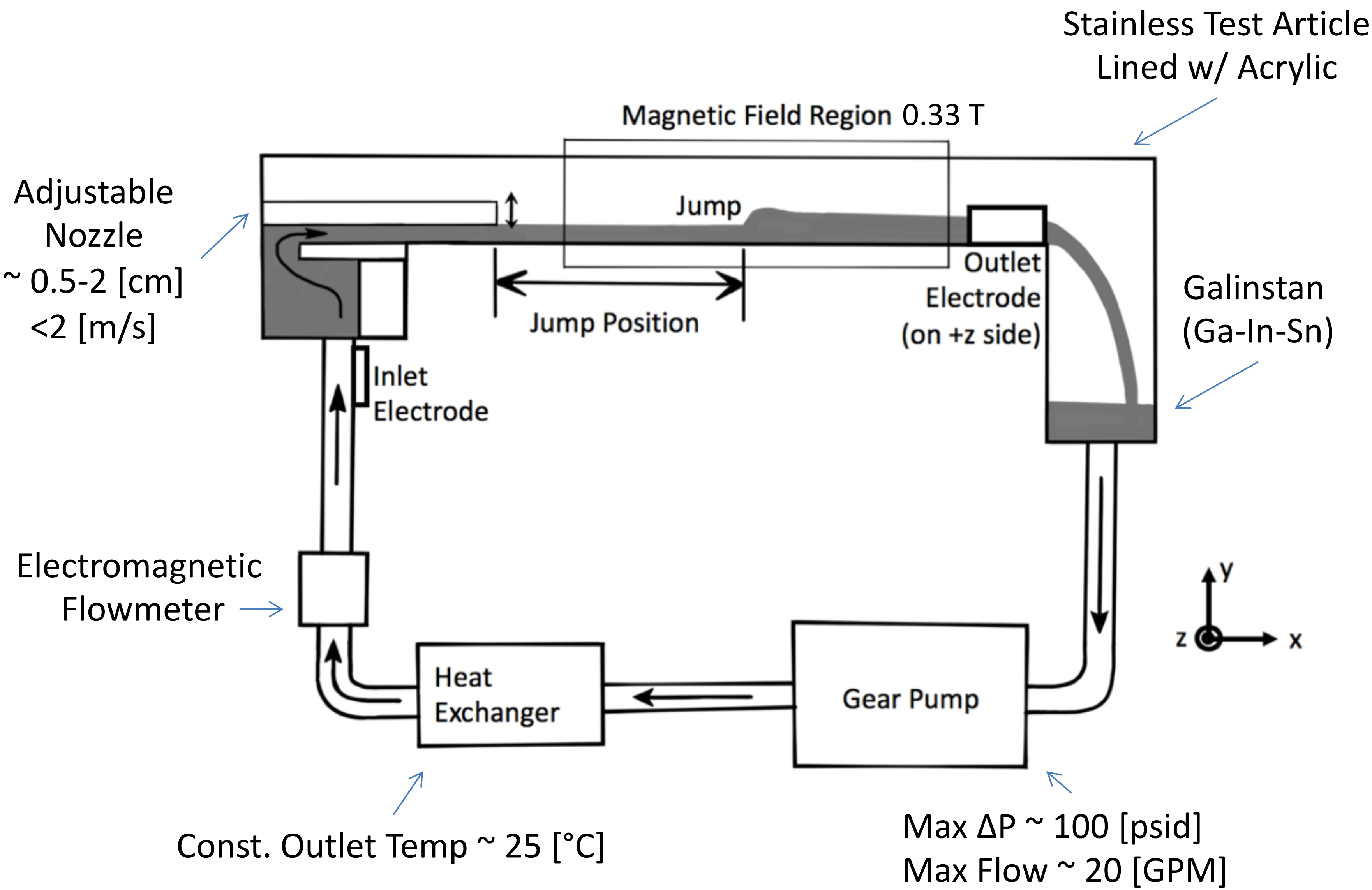
Liquid Metal Experiment (LMX) at PPPL

- LMX operating at PPPL (Kolemen Group)
- **Aim:** Understand LM flow at small scale
- Developing diagnostics and control for LM flow
  - Surface waves: Measurement and stabilization
  - Heat transfer: Enhance mixing using vortex generators
  - Holding Study jxB forces control of the LM flow and pumping

LMX publications by Kolemen group:

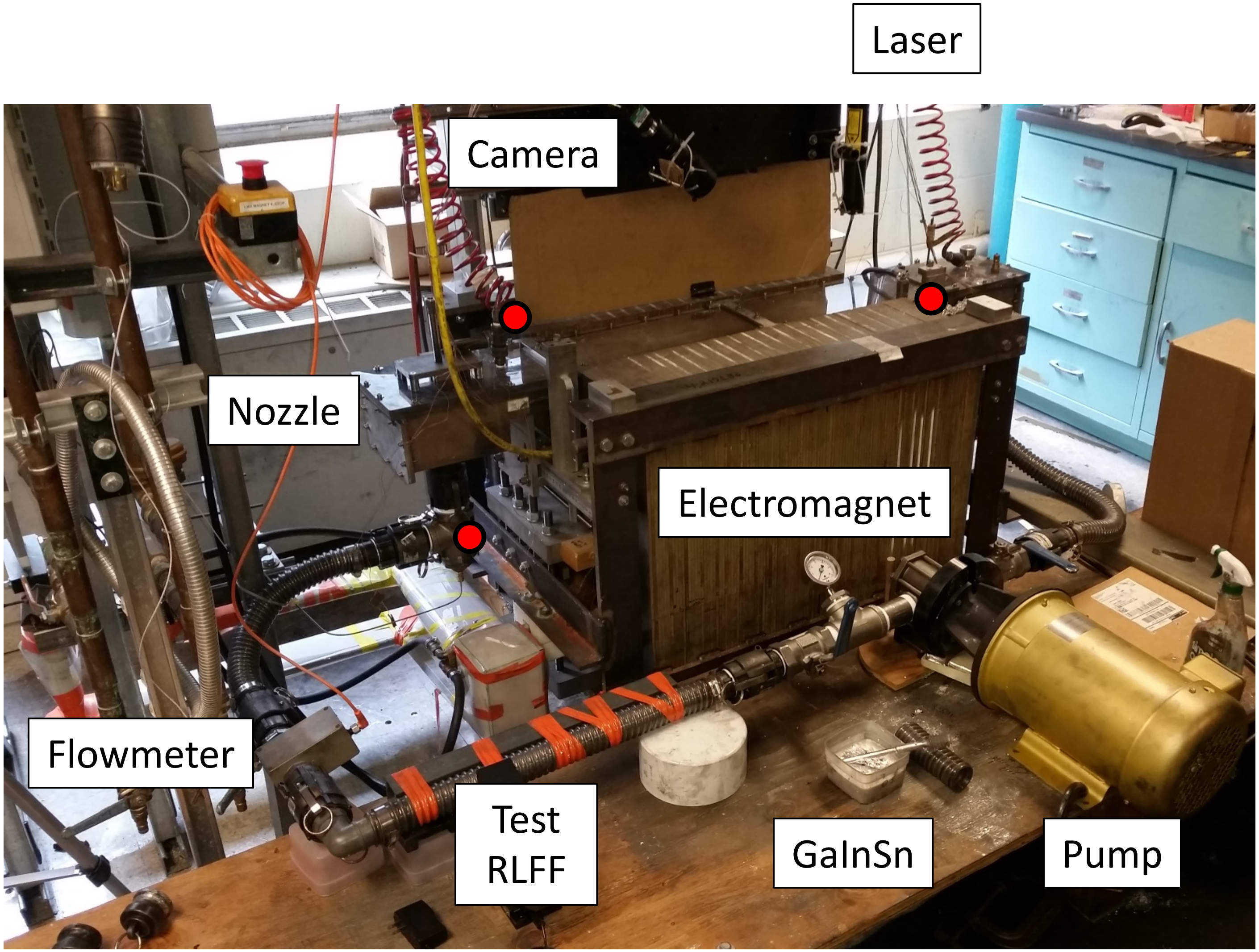
1. Kusumi, FEDC 111 1193 (2016)
2. Kusumi, FEDC 72,4, 796 (2017)
3. Kusumi, FEDC 01, 067 (2018)
4. Hvasta, RSI 88 013501 (2017)
5. Hvasta, Nucl. Fusion, (2017)
6. Hvasta, MST (2017)
7. Hvasta, MST (2018)
8. Hvasta. FST (2019)
9. Modestov, Nucl. Fusion, (2017)
10. Fisher, Phys. Fluids (2018)
11. Fisher, NME, 19, 101-106 (2019)
12. Kolemen, NME (2019)

LMX Schematic:



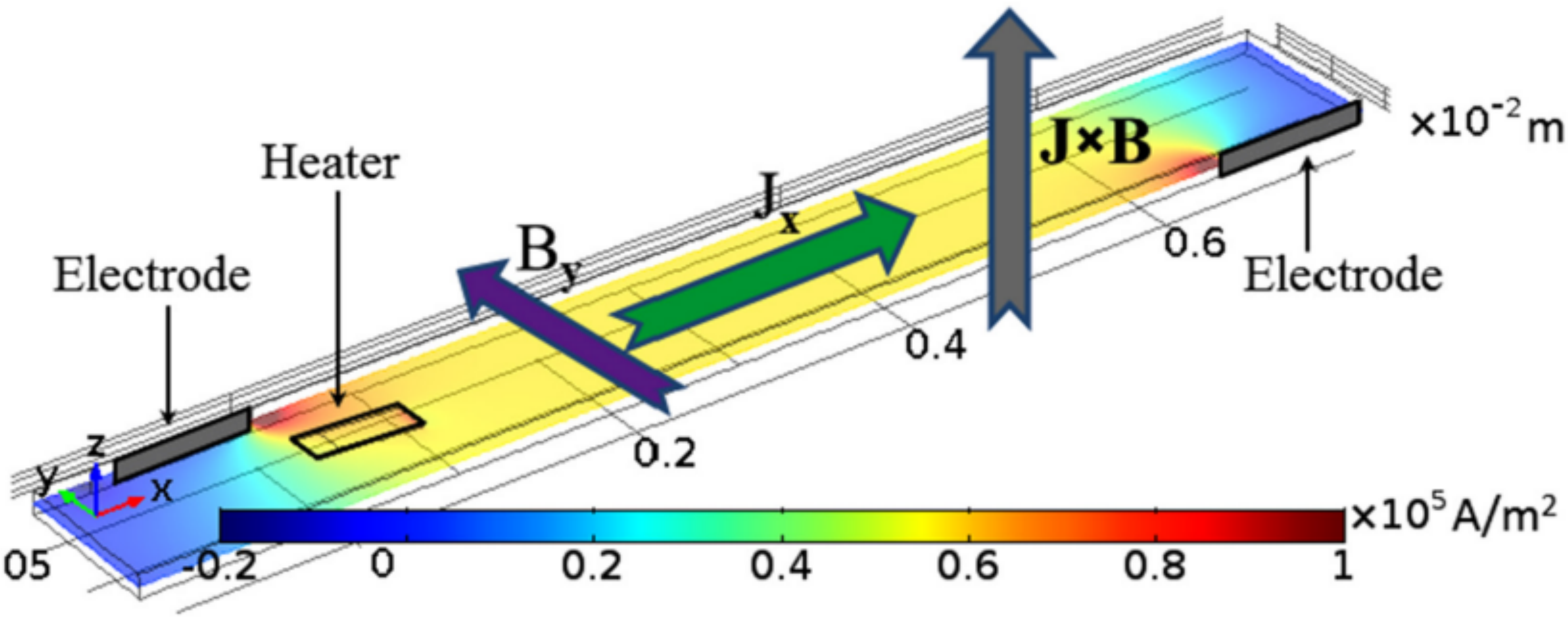
A. E. Fisher et al, Physics of Fluids 30, 067104 (2018)

LMX Photo:



● = Electrode Location

LMX Allows LM Experiments with Different Magnetic Fields and Electric Currents



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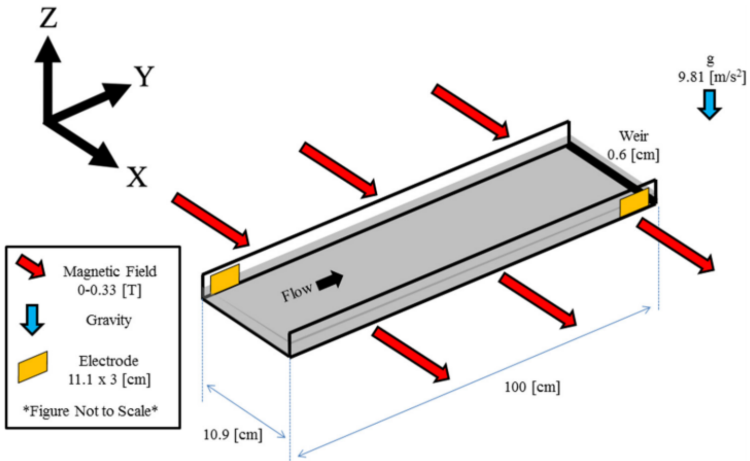
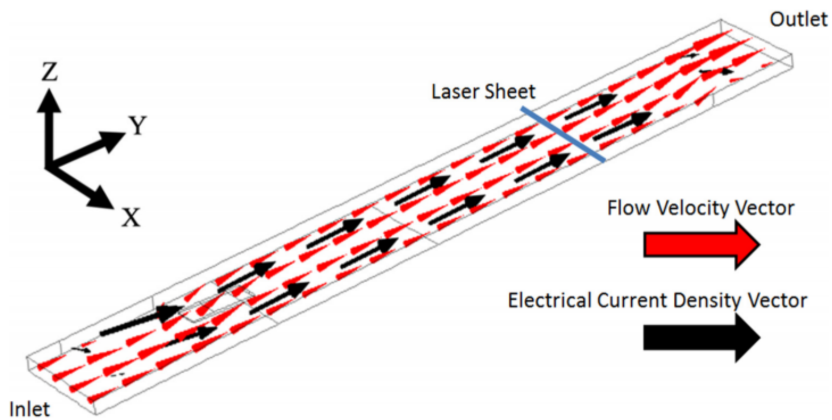




*Axes not labeled the same on all drawings in this presentation.

- Electrical current densities depend on fluid depth (I_{Max} = 140 [A])
    - Typical range ~ 5e4 [A/m²]
    - $\frac{j\,B}{\rho\,g} \sim$ 0.3-0.5 (direction depend.)
- Electrical current is largely uniform in the middle of the duct

<u>Lithium:</u>

$$\overbrace{\rho g}^{\text{Gravitational Force}} = \overbrace{jB}^{\text{Lorentz Force}}$$

$$500\ \left(\mathrm{kg\ m^{-3}}\right)\ 9.8\ \left(\mathrm{m\ s^{-2}}\right) = j\left(\mathrm{A\ m^{-2}}\right)\ B\,(\mathrm{T})$$

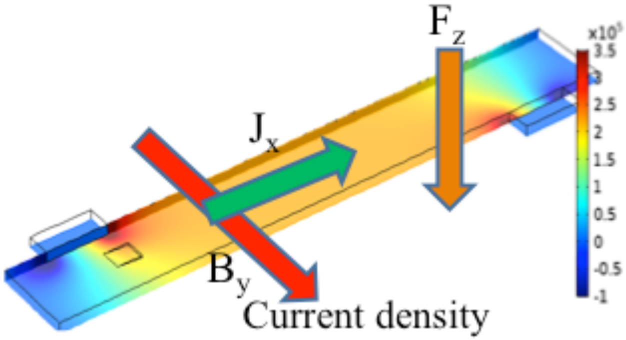
Table 1. The current density within a liquid lithium PFC required to exert a body-force equal to gravity ($g = 9.8\ (\mathrm{m\ s^{-2}})$) for various fusion reactors.

Reactor/Ref.	Toroidal magnetic field, B (T)	Approx. current density, j (A m^{-2})
NSTX-U/[21]	1	4900
ITER/[22]	5.3	920
DEMO/[23, 24]	5.86–6	840–820

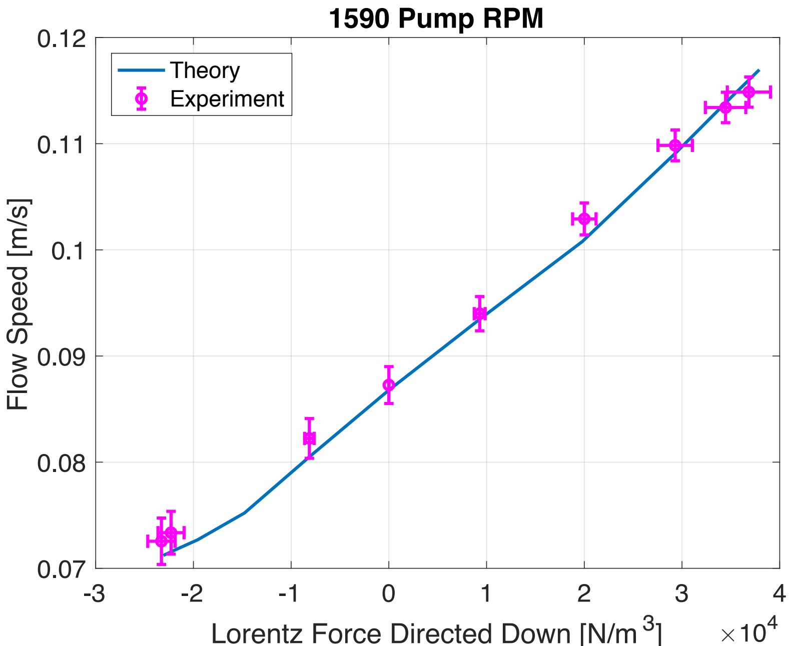
Control of Velocity Achieved with Current in LM

- **jxB affect model for bulk flow:**
  - Mass conservation: $\boldsymbol{u_1 h_0 = v_1 h_1 = Q}$
  - Momentum conservation:

$$\rho v_0^2 h_0 + \frac{\rho g h_0^2}{2} = \rho v_1^2 h_1 + \frac{\rho g h_1^2}{2} + \frac{\boldsymbol{jBh_1^2}}{\boldsymbol{2}}$$

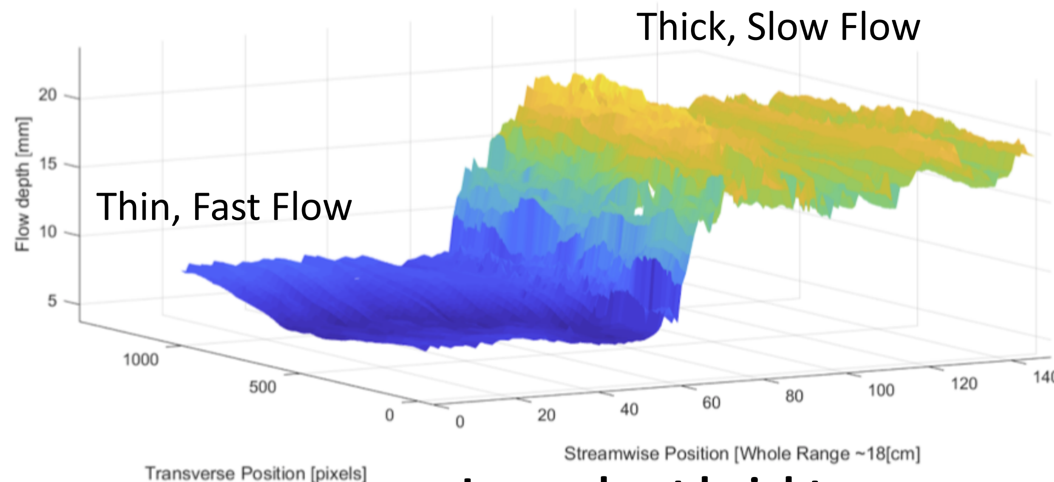


- **Proof of principle: We can get >>g in a reactor**



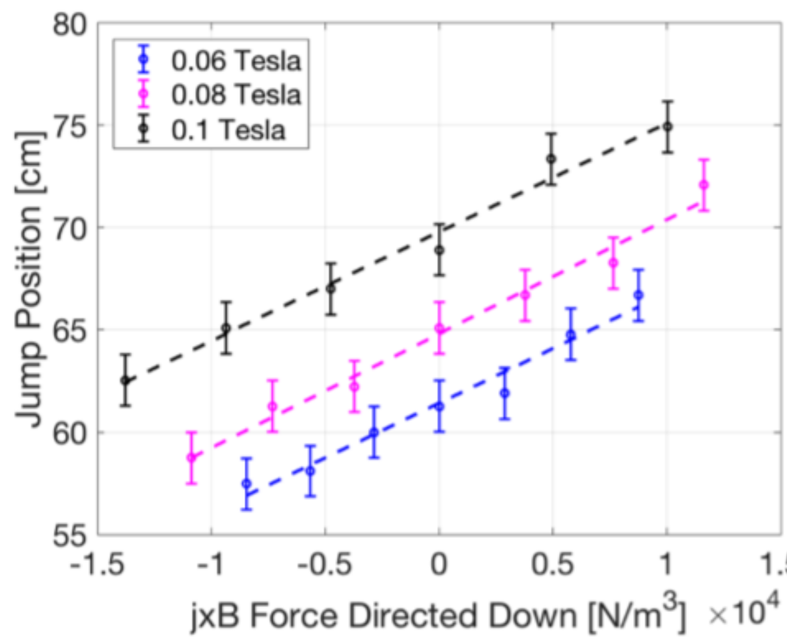
Control of Hydraulic Jump Achieved with Current in LM

$Fr = u/\sqrt{gl}$: ratio of flow inertial to external field (g). Fr>1 supercritical flow, fluids “jumps” to lower speed, higher height, low energy state (subcritical)



Laser-sheet height measurement

Control of the hydraulic jump location using externally applied jxB forces.



A. E. Fisher et al, Physics of Fluids 30, 067104 (2018)

Vortex Generator Can Enhance Heat Transport

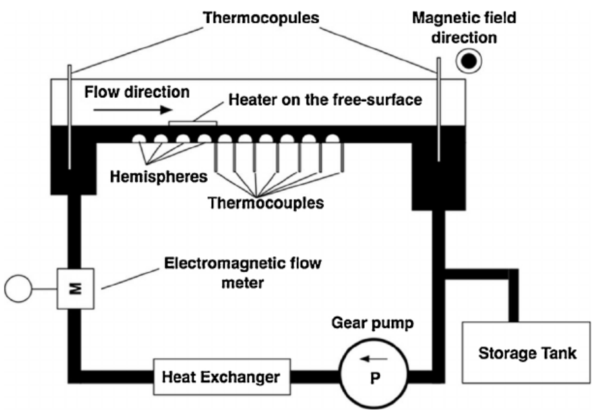
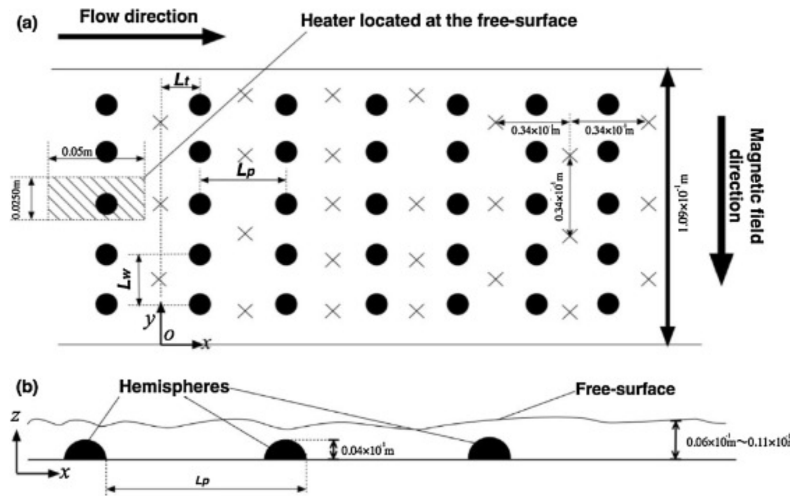
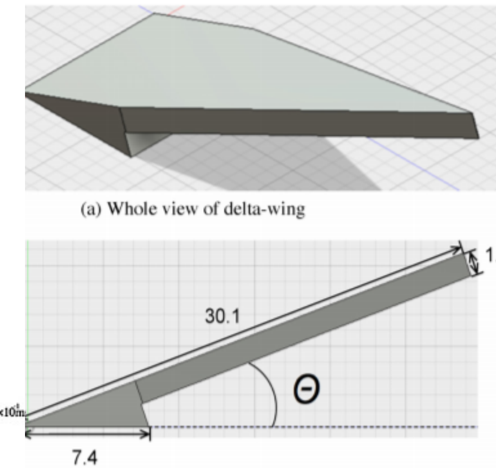


Fig. 1. Experimental apparatus (black area is working fluid; white area is injected argon gas).

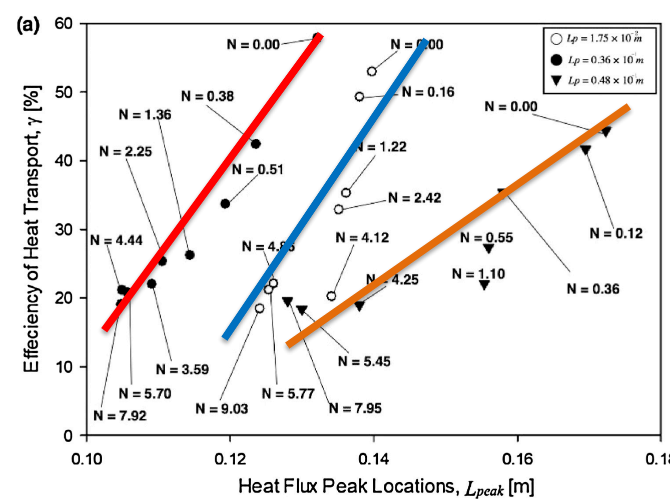




(a) Whole view of delta-wing

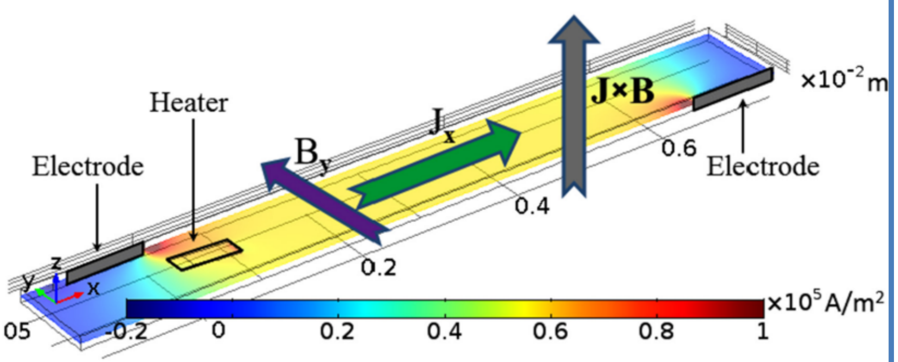
(b) Cross-section view of delta-wing

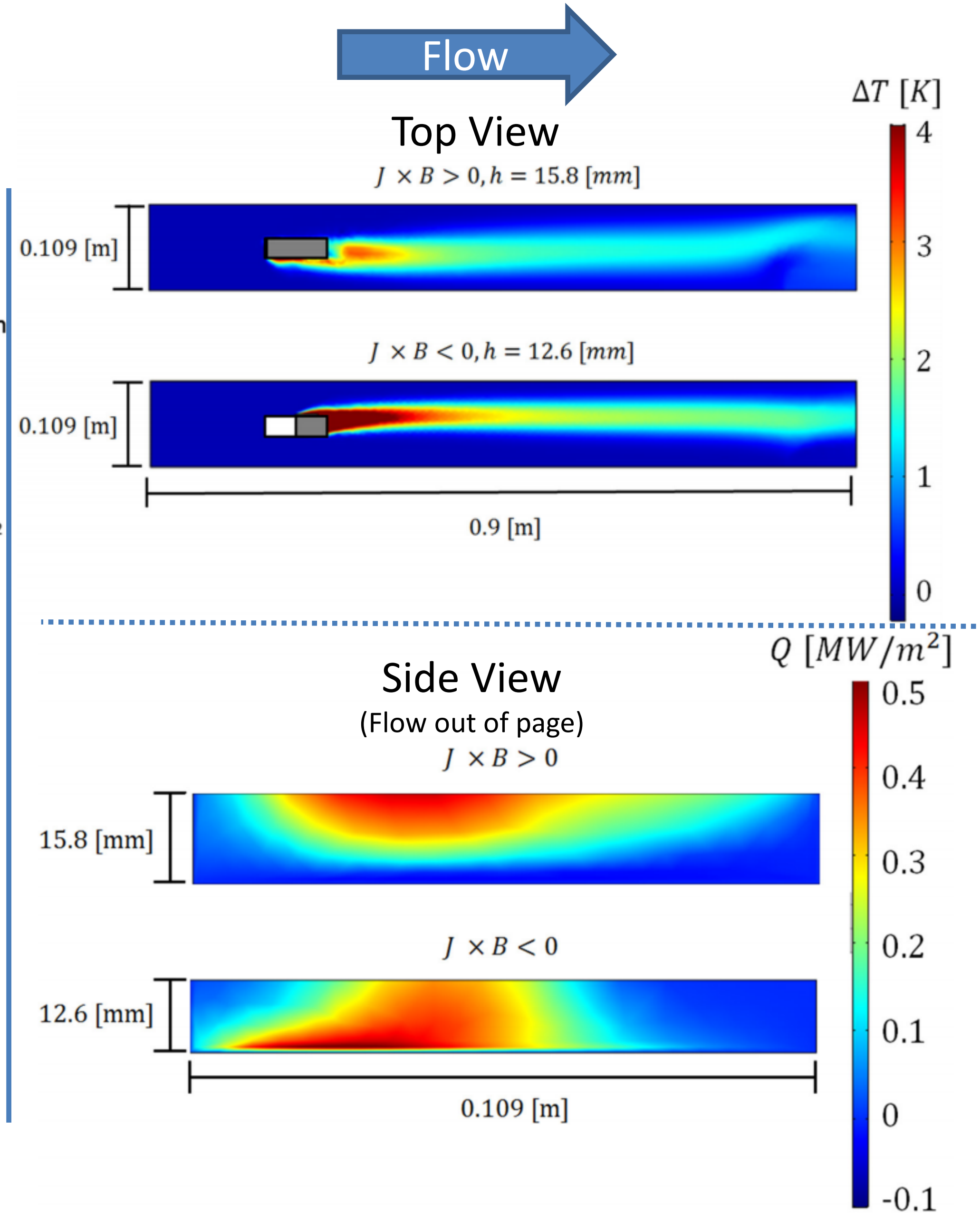
- Enhanced heat transport and reduced speed requirement
- $\mathbf{u_{unmixed}/u_{mixed} \sim 10}$
- Different surface bumps and vortex generators
- Studies heat transfer from the top to bottom
- Limit surface temp / evaporation



K. Kusumi et al, Fusion Engineering and Design **2016, 2017 and 2018**

Active Control of Heat Transport Achieved with jxB



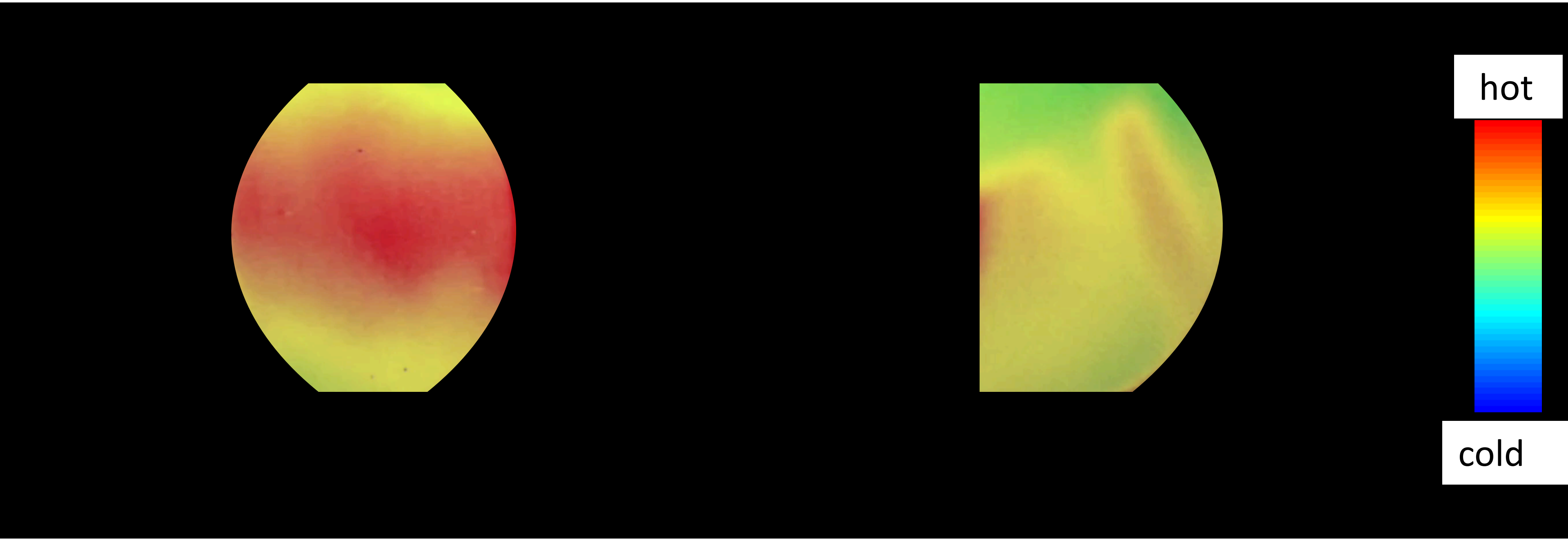


- **Heat transport can be controlled by jxB force gradients near electrodes.**
- **Shows the trends from experimental Temperature measurements**

Modestov et al, Nucl. Fusion 58 (2018) 016009 (9pp)

Current in LM Can Enhance the Heat Convection

- jxB gradient causes mixing in flow, improving heat flux to the bottom and sides of the channel. (A. Fisher and J Hinojosa).



Thermal Camera on top of the flow

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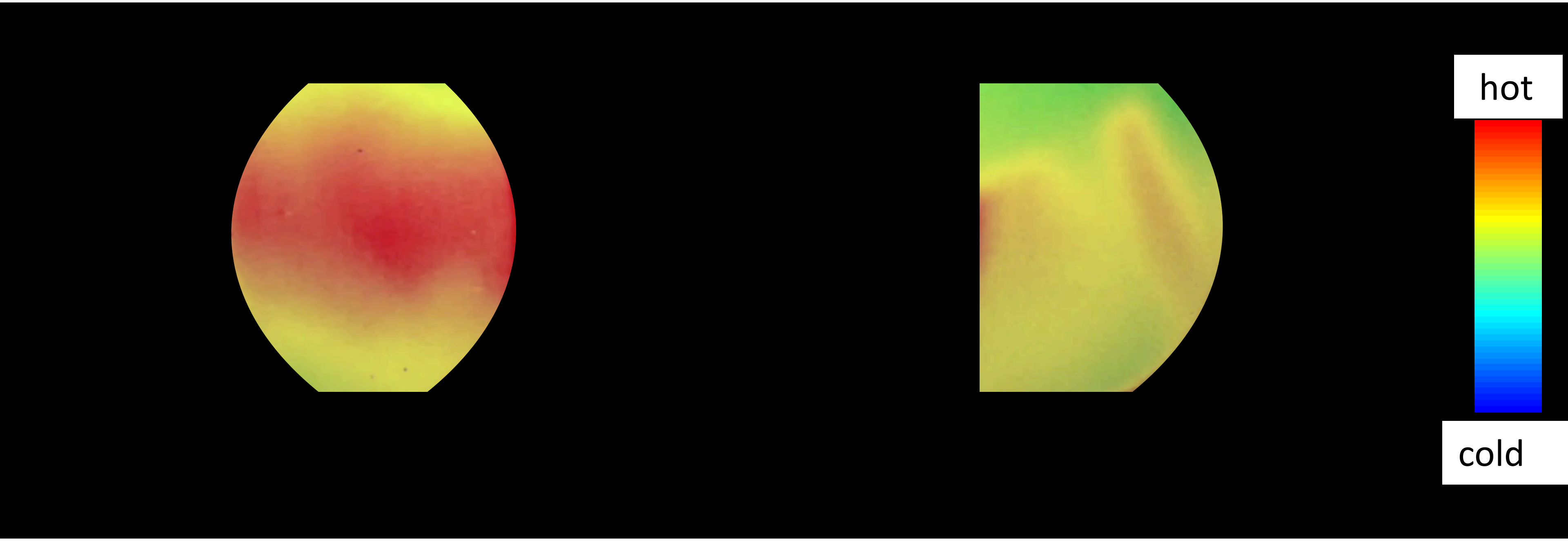


Thermal Camera on top of the flow

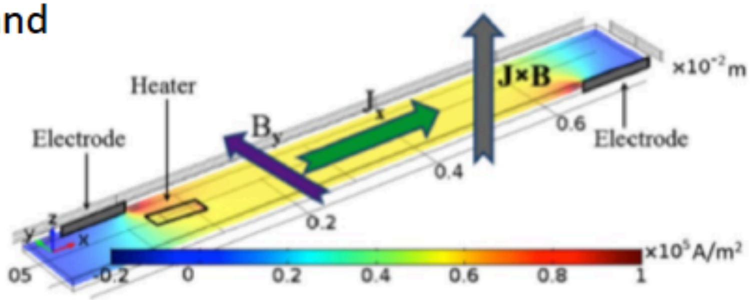
Upgrades to Liquid Metal Experiment (LMX) – Chute Experiments are Critical to Flowing Liquid Metal Technical Basis

Offline facilities are effective platforms for establishing the physics and technical basis for flowing LM PFCs (and capillary concepts, etc)

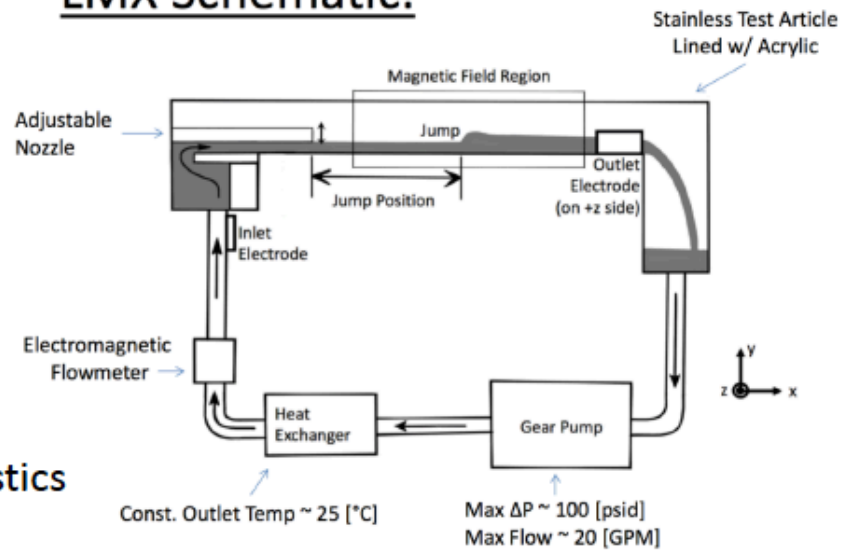
Vacuum enclosure for LM flow path
Chute length, different chute geometries, incline
B-field increase, B_{rad} with coils or perm. magnets
Increase temperature, replace plastic parts
Heat LM from above, like a plasma
Test multiple substrate materials
Test other LMs than Galinstan (Sn, Sn-Li, Li)
Flow around obstructions like ports
Nozzle optimization
LM cleanup systems in loop
Flow speed
Easy tear-down and rebuild

Test simulation predictions with detailed diagnostics

Prototypic experimental apparatus



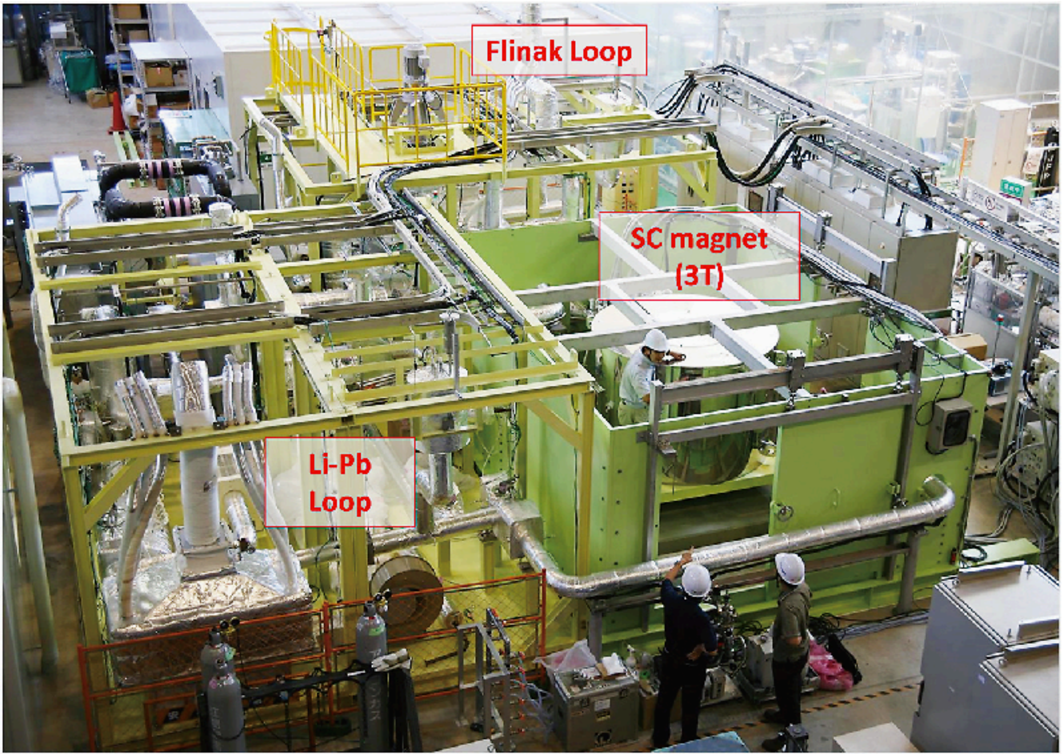
LMX Schematic:

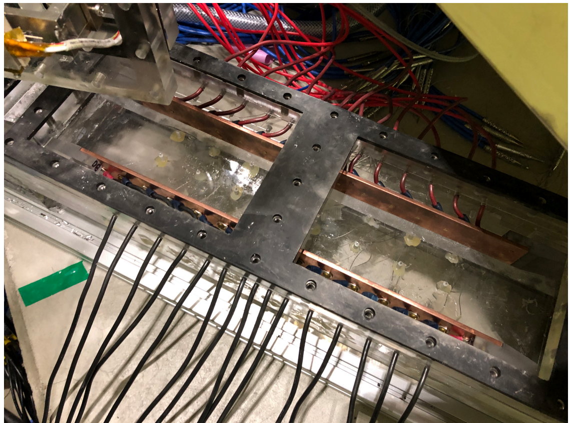


Kessel, FESS LM Study Presentation

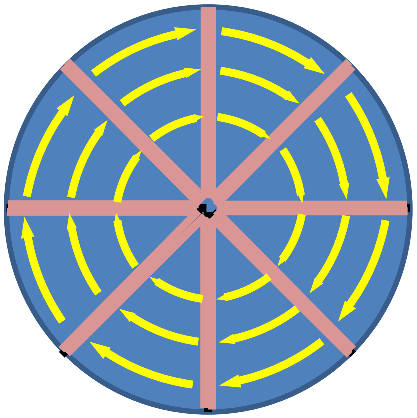
Fast LM Experiments at Oroshhi-2, Japan

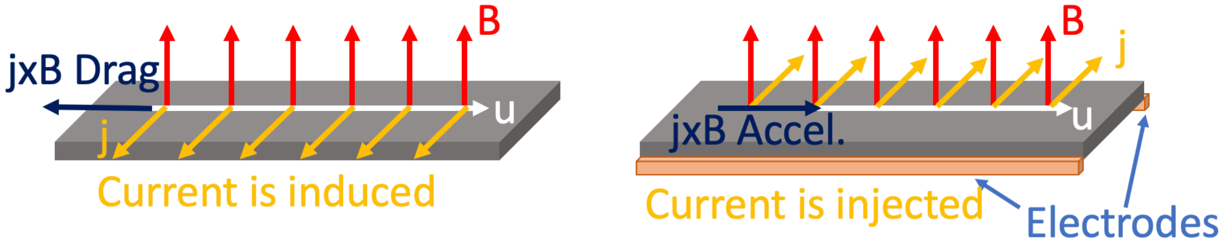
A. Fisher, T. Tanaka , T. Kunugi, J. Yagi, T. Hamaji, K. Kusumi, Y. Go, G. Yamazaki, E. Kolemen

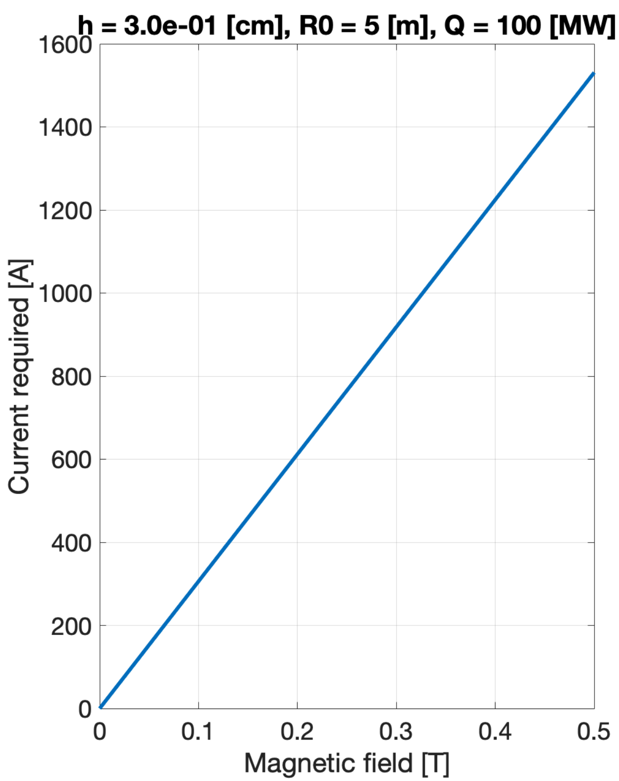




Overcoming MHD Drag with J_{tor} (A. Fisher)





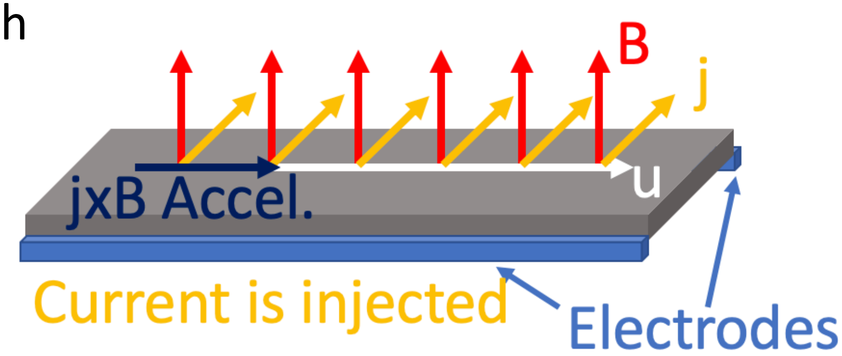


- MHD drag due to vertical B is an issue, but how bad is it?
- Chuck Kessel asked to look at cassette configurations. If we can have toroidal separation, we can run $\mathbf{J_{tor}}$
- Setting drag=forcing, and require velocity from heat flux

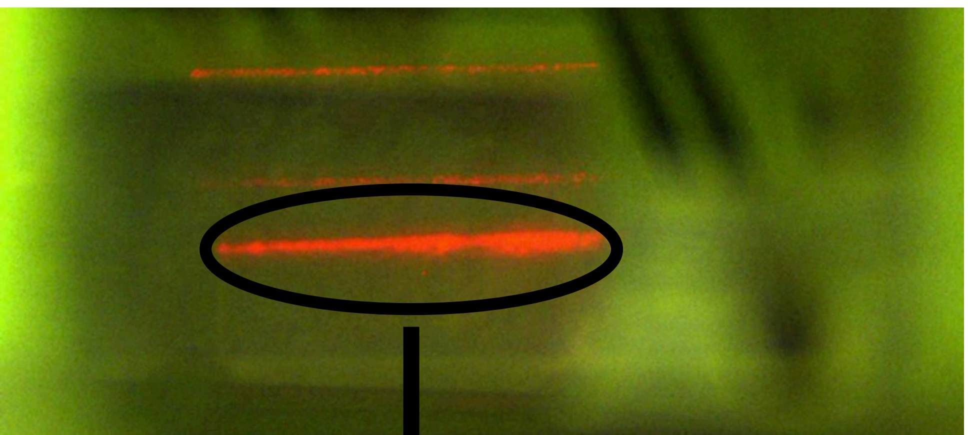
  ➔ $j \;\alpha\; B_{ver}\, Q^2$ (not dependent on divertor length)
- **Required total current is very low**

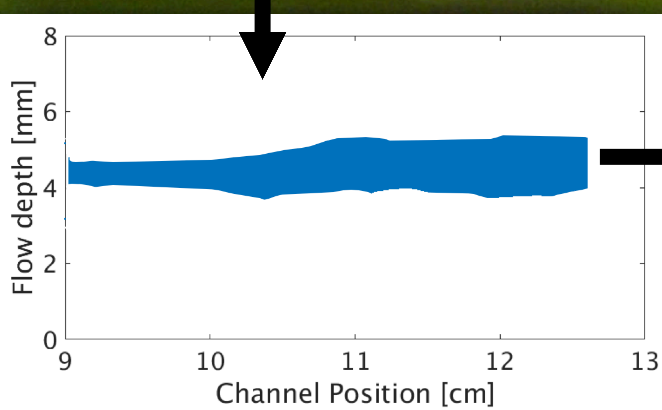
J_{tor} Induces MHD Thrust ➔ Increase Flow Speed (A. Fisher)

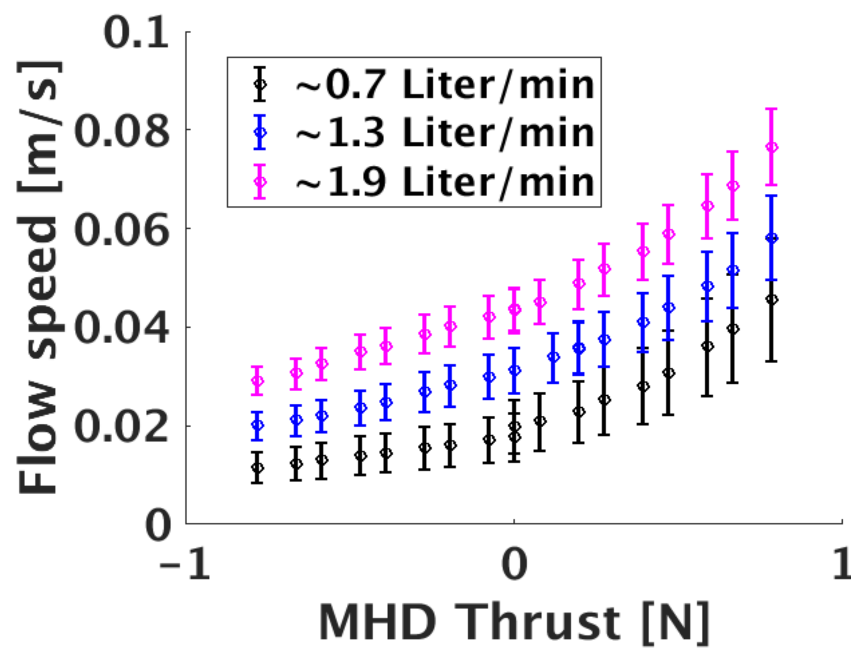
- Orosshi-2 (NIFS, Japan) experiments with Kyoto University LMFREX channel
- **Electrodes to produce jxB force along u**
- At high fill (high h and B_{vert} 0.6 T)



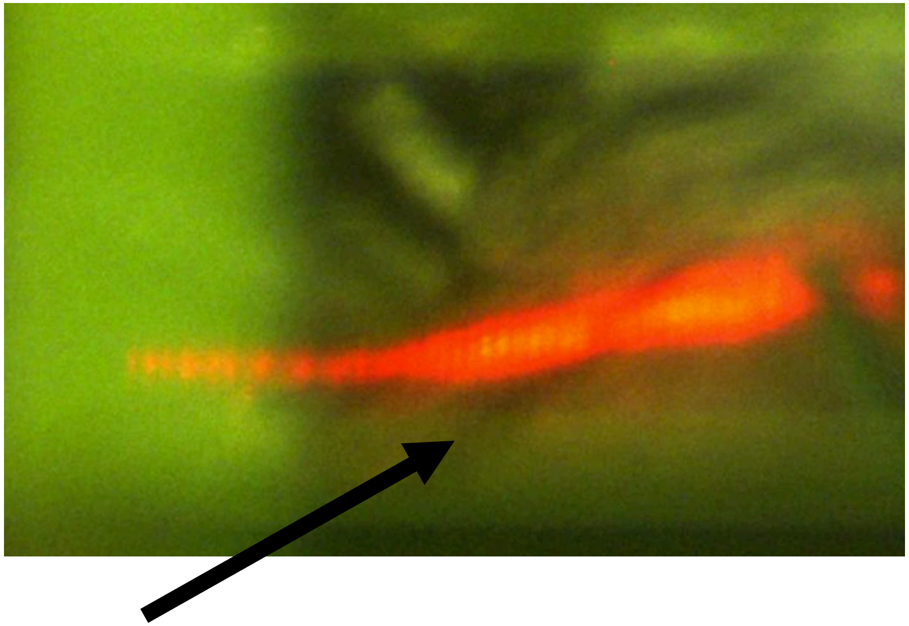
Flow is from right to left, force directed to the left





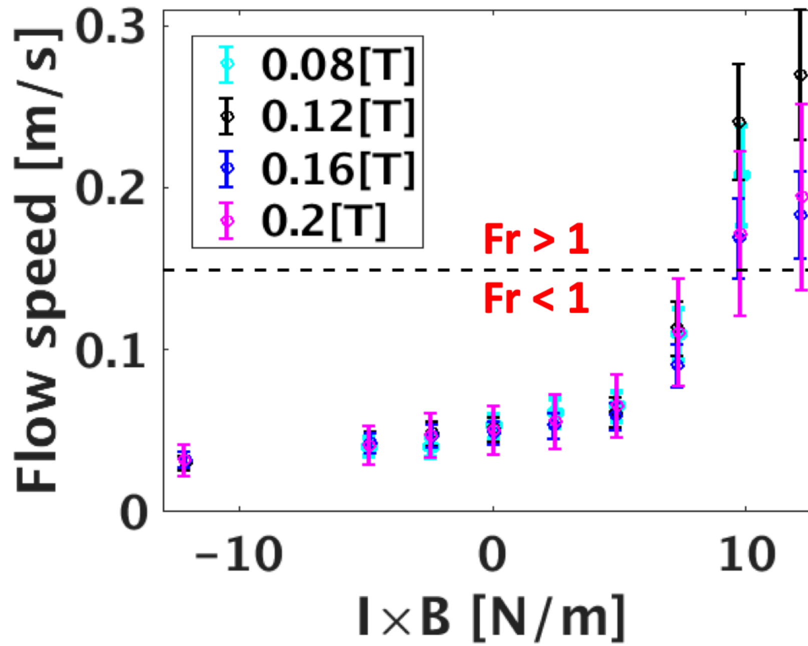


MHD Induced Speed Increase Can Lead to Hydraulic Jump (A. Fisher)



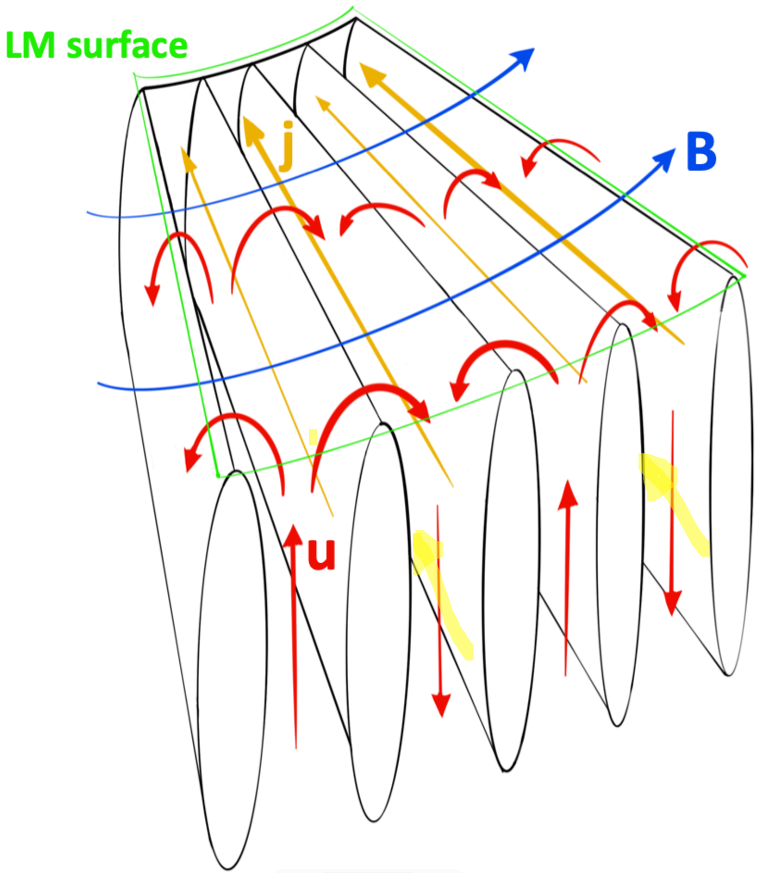
Hydraulic jump

Thin LM flow



- Higher speed from MHD thrust leads to hydraulic jumps in thin flow
  - When Fr number becomes greater than 1
  - Increasing MHD drag from higher magnetic fields requires a larger accelerating force.

Divertorlets



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

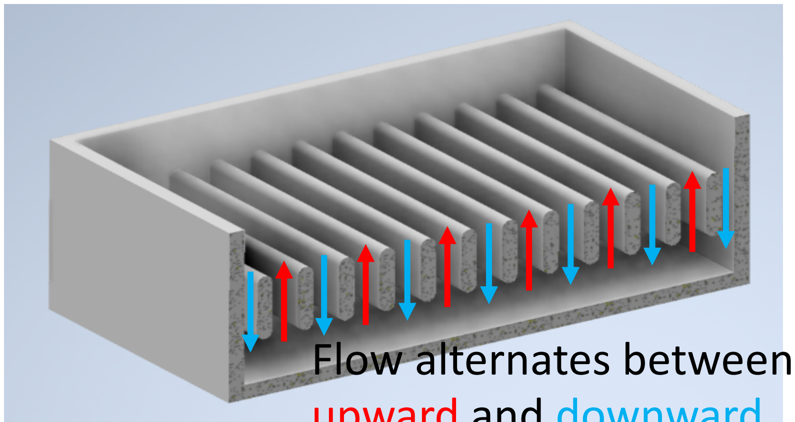
$$v = \frac{L}{t_{rc}}$$

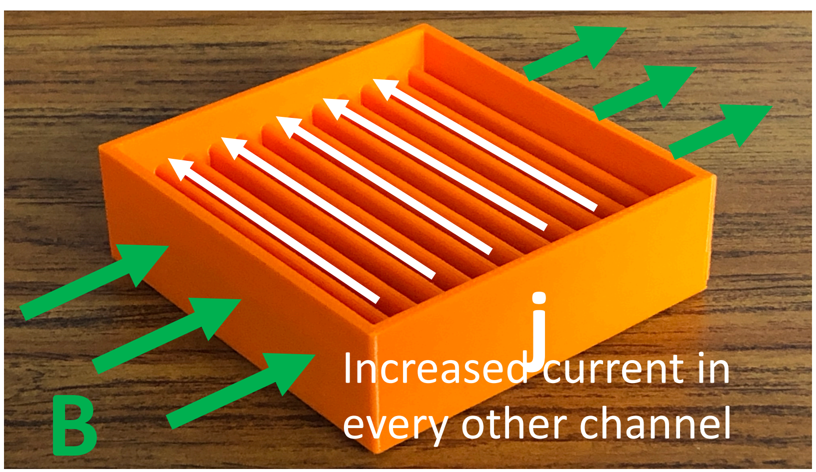
- ↓ L ➔ ↓ v (m/s ➔ cm/s)
- Reduce drag, reduce splashing
- Possible to use simpler flowing setups

- Looking at many options
- Mainly use of jxB

- Ex: J_{pol} every other trench and on surface

Divertorlets





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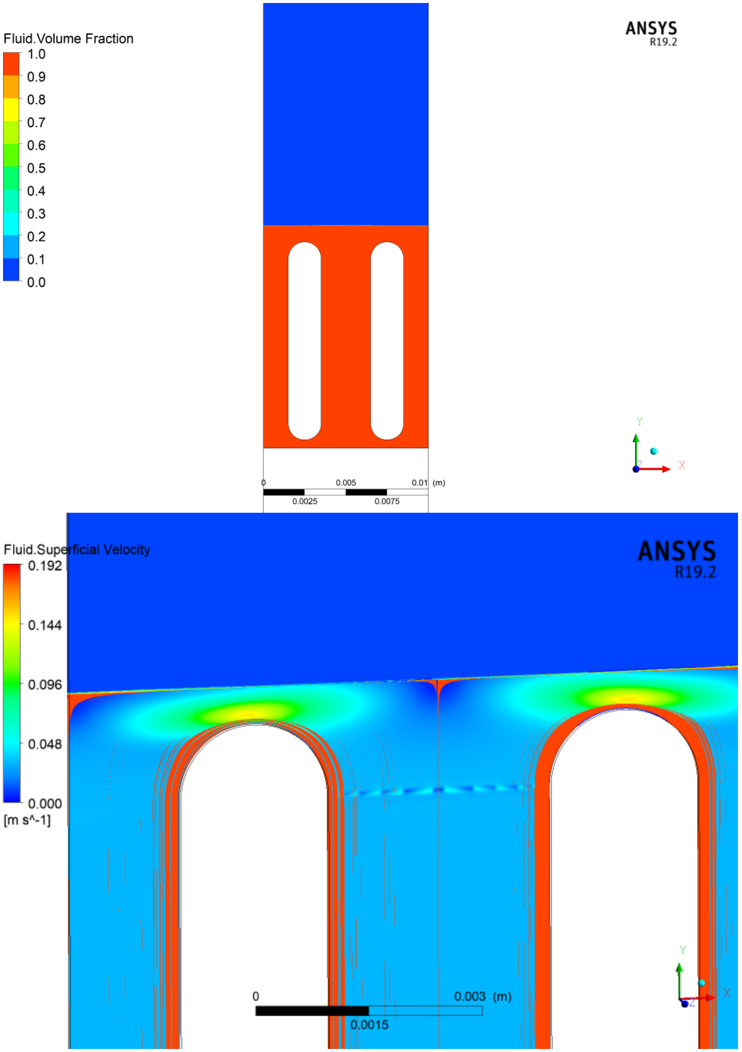

Example flow simulations showing
Stable flow w/ setup
(A. Khodak)

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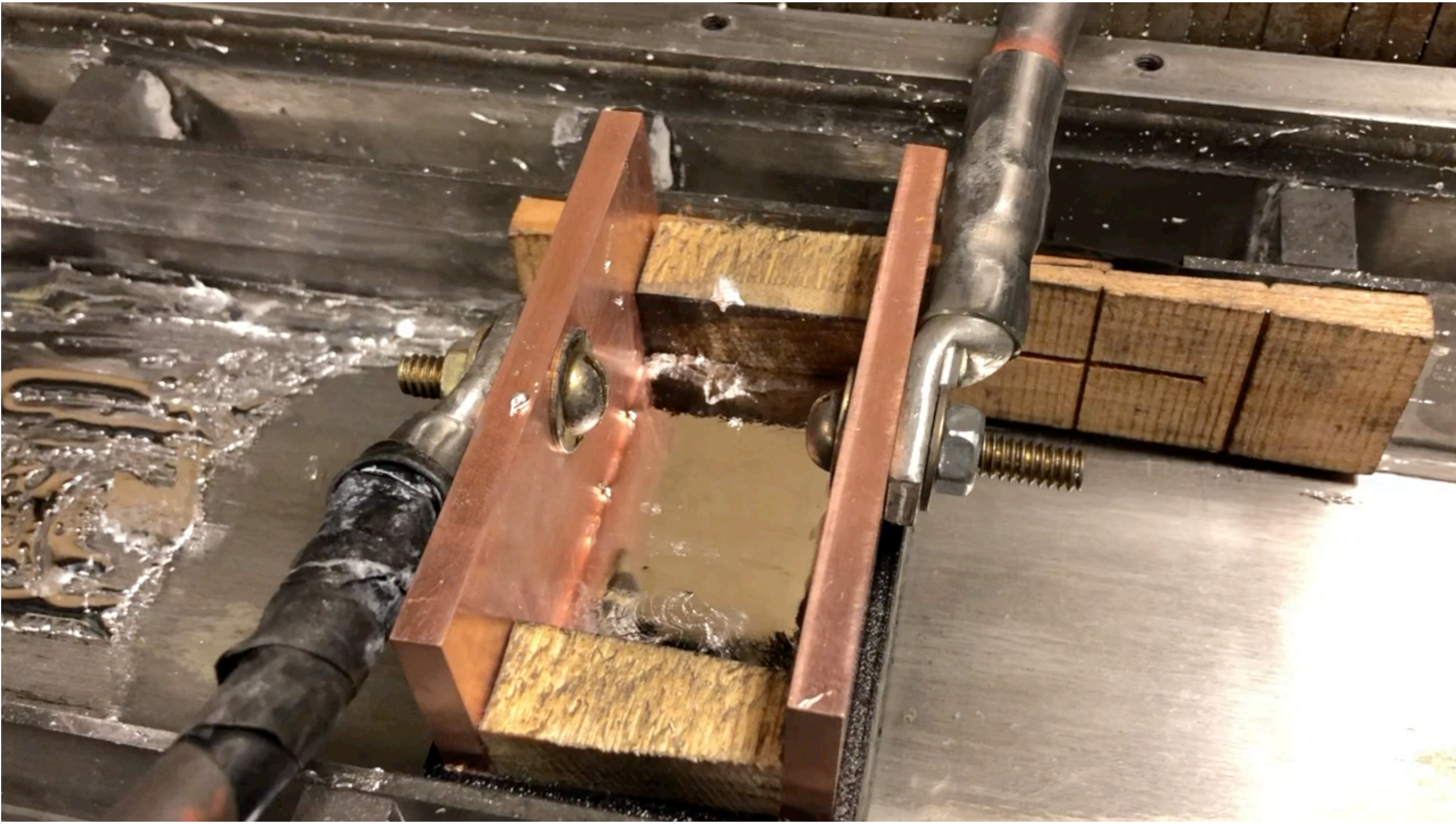
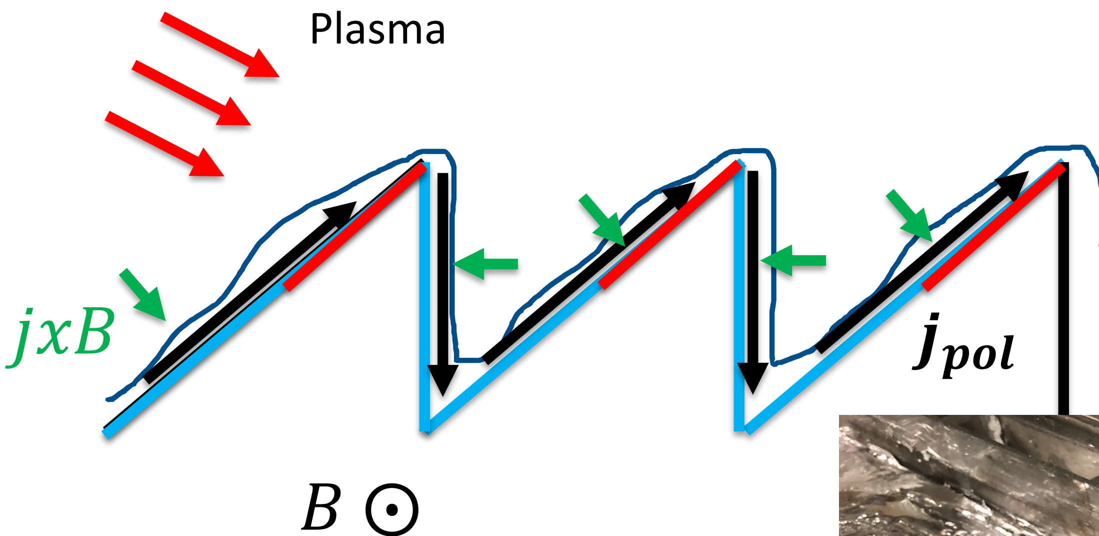
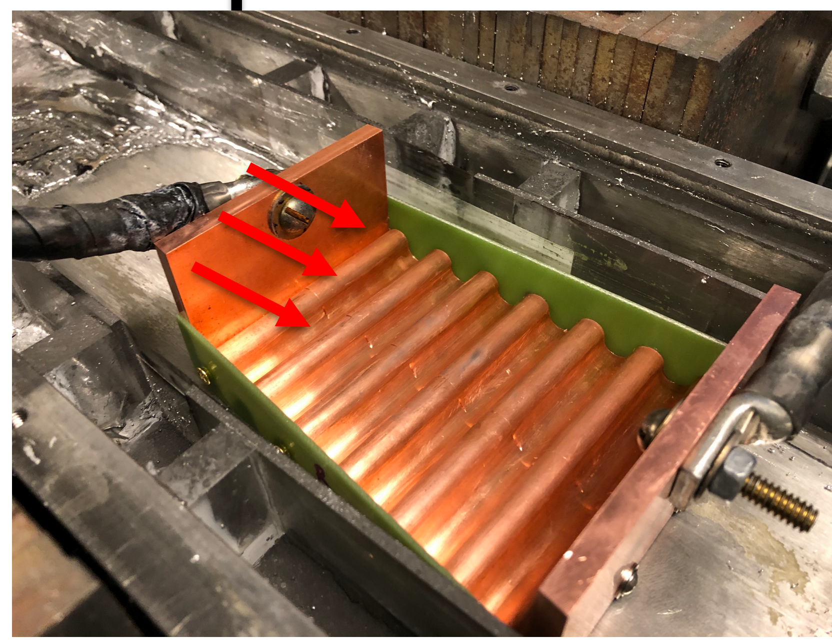


Divertorlets

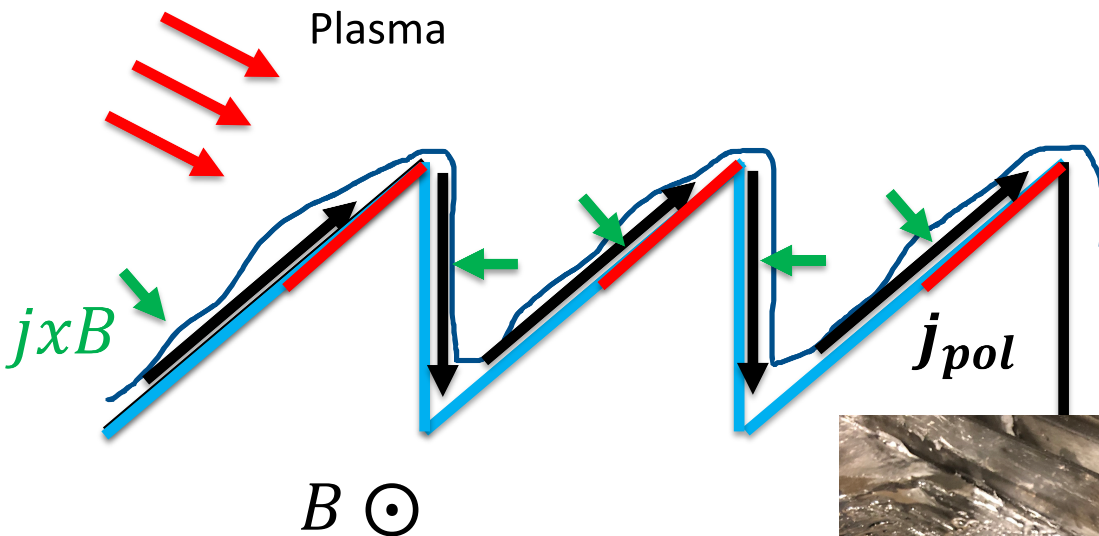




- **Cool the LM in the down sections to keep the temperature down (cooling surface).**
- **Allow for T ↓ ➔ v ↓**

$$t_{cr} = (\Delta T/2q)^2 \pi k \rho c_p \qquad v = \frac{L}{t_{rc}}$$

Divertorlets



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Separation LiD/LiT before leaving the vessel (Patent disclosure Kolemen & Majeski)

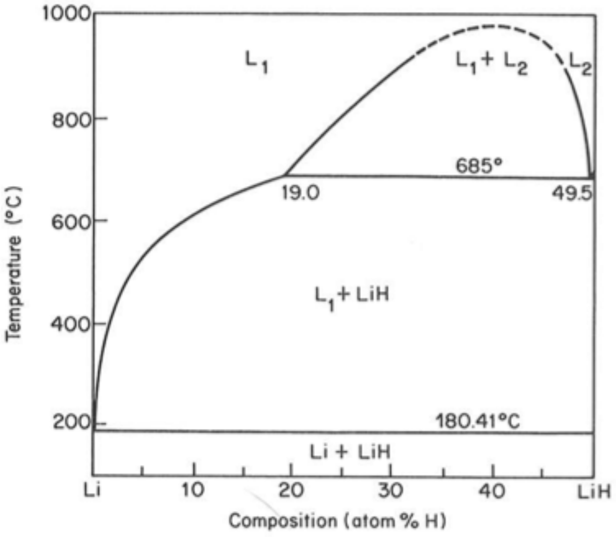
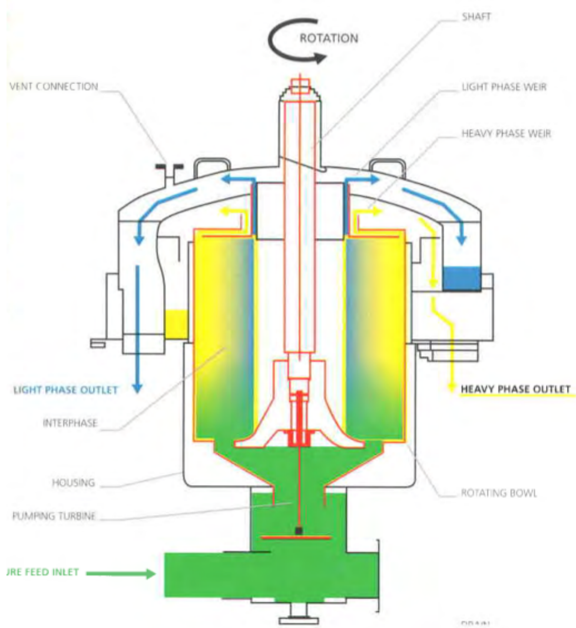
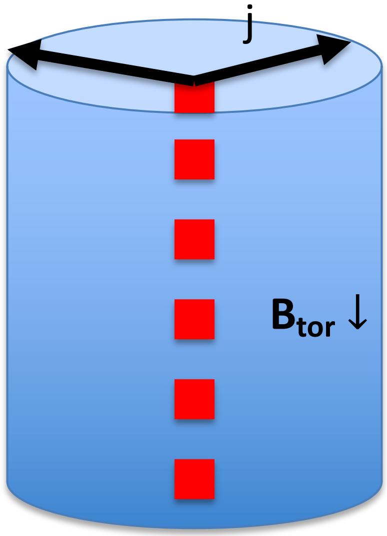


Figure 5.3 Lithium–lithium hydride phase diagram





- Solubility of hydrogen in lithium falls rapidly with temperature
  - 0.3 At. % at 300 ˚C ⇨ 0.044% at 200 ˚C.
- LiD, LiT will be formed
- Density of LiD, LiT *twice* liquid lithium
- Separation via magnetic centrifuge (We have B in tokamak, need to run j in a cylinder)
  - Centrifuges would operate at ~190˚C
  - Enriched slurry of LiD, LiT removed continuously at periphery
- **Flow to tritium separation unit (miniscule) ↓ ➔ MHD drag ↓ ➔ Power ↓**

Conclusion and Future Perspective

- US LM FNSF Study concluded → US LM Divertor Program started
- FNSF design needs more detailed experimental studies of MHD issues related to LM flow.
  - Check simulation projections against experiments
- In LMX and Oroshhi-2, we studied flow instabilities and showed control of
  - Velocity/Height
  - Heat Transport
  - Hydraulic Jump
- These insight will allow us to find the optimal LM flow and J, current, setup for FNSF.
- LMX Upgrade will allow to cover important MHD phase space
- FLIT designed/reviewed at PPPL for realistic LM flow experiments
- Divertorlets are possible options to reduce engineering requirements