Experimental Demonstration of Lorentz Force Propulsion on Free-Surface Liquid Metal Channel Flow

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

Princeton University, National Institute for Fusion Science, Kyoto University, Princeton Plasma Physics Laboratory

Motivation

Fast-flowing liquid metal divertor concepts look to solve problems faced by solid divertor components such as melting and/or deformation. However, if the liquid metal decelerates and evaporates excessively it can result in plasma disruption. The setup & allowable exposure is shown in Figure 1. By injecting an electrical current through the flowing liquid metal to create an accelerating force, the MHD drag can be countered. This is plotted in Figure 2, with required current density *(j)* shown below:

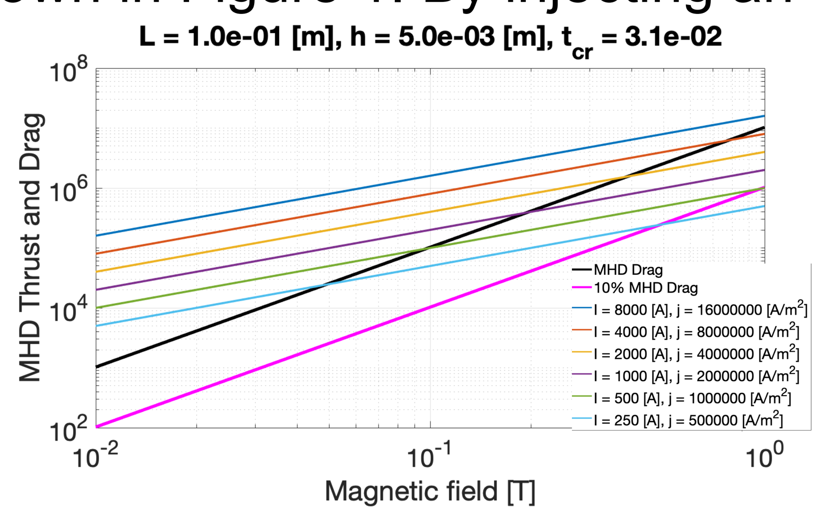

Figure 2. MHD drag vs. MHD thrust at various conditions

$$j = \frac{4C_M \sigma B L Q^2}{\pi^3((r_0+L)^2 - r_0^2)^2 \Delta T^2 k \rho c_p}$$

B: magnetic field
Q: flow rate
r_0: divertor inner radius
L: length of liquid metal flow
C_M: coefficient of MHD drag

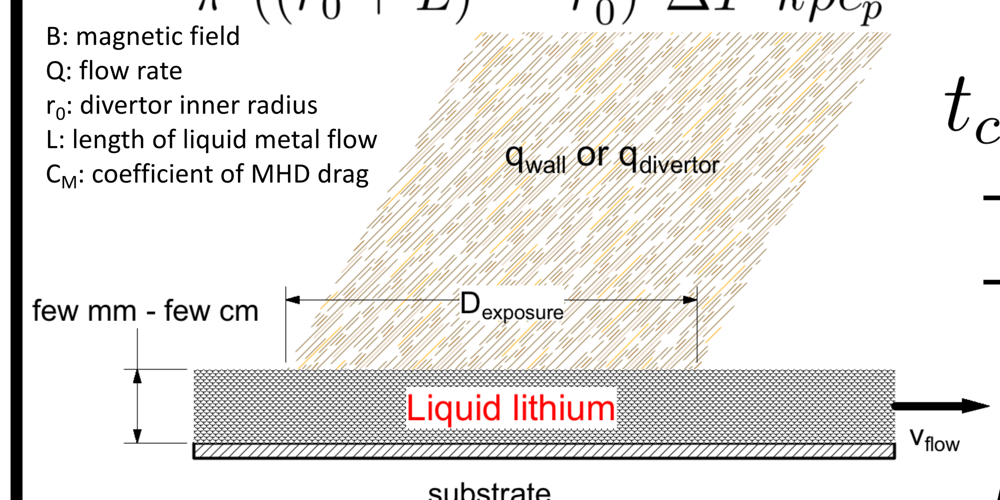

Figure 1. Schematic of plasma heat flux on flowing liquid lithium [1]

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

$\Delta T = 200[\mathrm{K}], q = 10\left[\frac{\mathrm{MW}}{\mathrm{m}^2}\right]$, Li @ ~300K

$k \approx 46\left[\frac{\mathrm{W}}{\mathrm{mK}}\right], \rho \approx 500\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right], c_p \approx 4310\left[\frac{\mathrm{J}}{\mathrm{kgK}}\right]$

LMFREX and Oroshhi-2

The LMFREX channel from Kyoto University was brought to NIFS to be placed within the Oroshhi-2 superconducting magnet. LMFREX is equipped with a heater and thermocouple array to study heat flux within MHD flows; it is a full acrylic channel that uses GaInSn as a working fluid. Oroshhi-2 is a flow loop that flows PbLi and FLiNaK in pipes/ducts through a 3[T] superconducting magnet to study MHD effects on the flow.

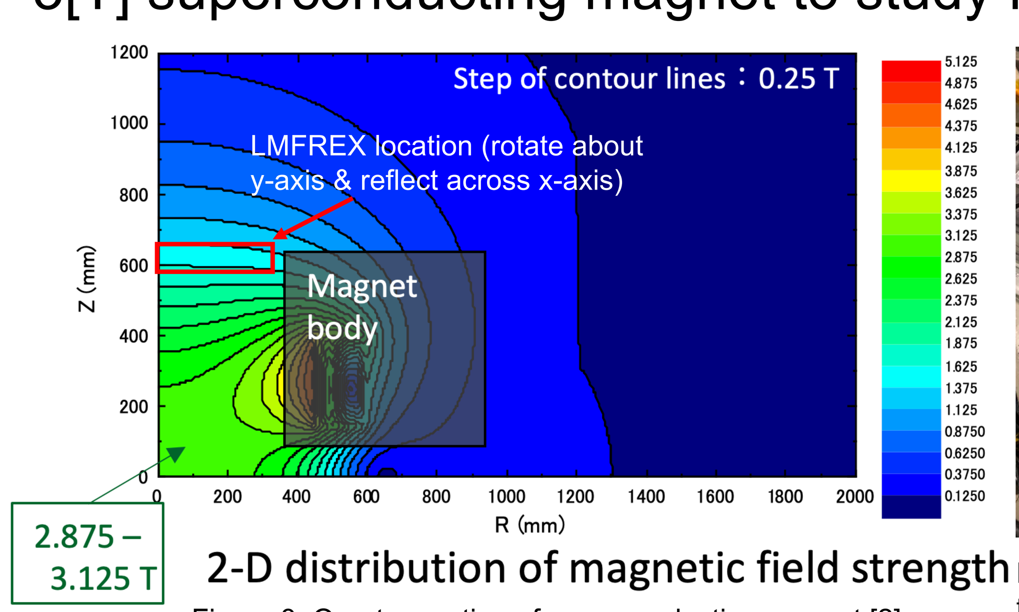

Figure 3. Quarter section of superconducting magnet [2]

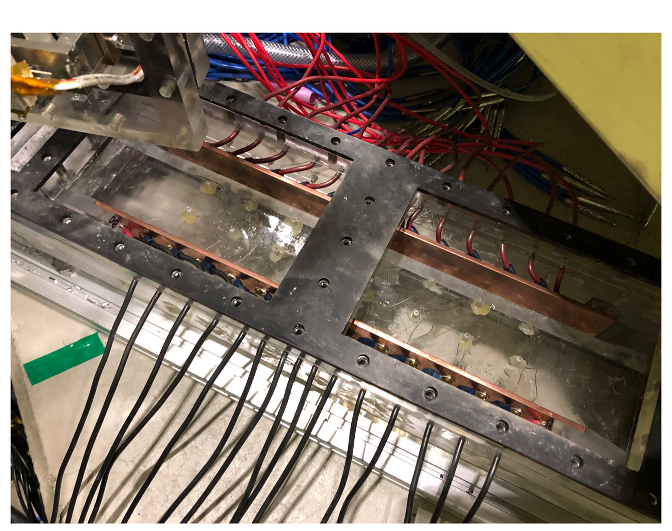

Figure 4. The LMFREX channel with wall electrodes, the electrode test section is 10[cm] wide, 30[cm] long

Free-surface Lorentz force propulsion

Lorentz force (jxB force) is a powerful tool that may be used for free-surface liquid metal flows. With a surface-normal magnetic field, a transverse electrical current may be used to create a jxB force aligned with the flow direction, and counter MHD drag. Other jxB force configurations have been studied on LMX-U.

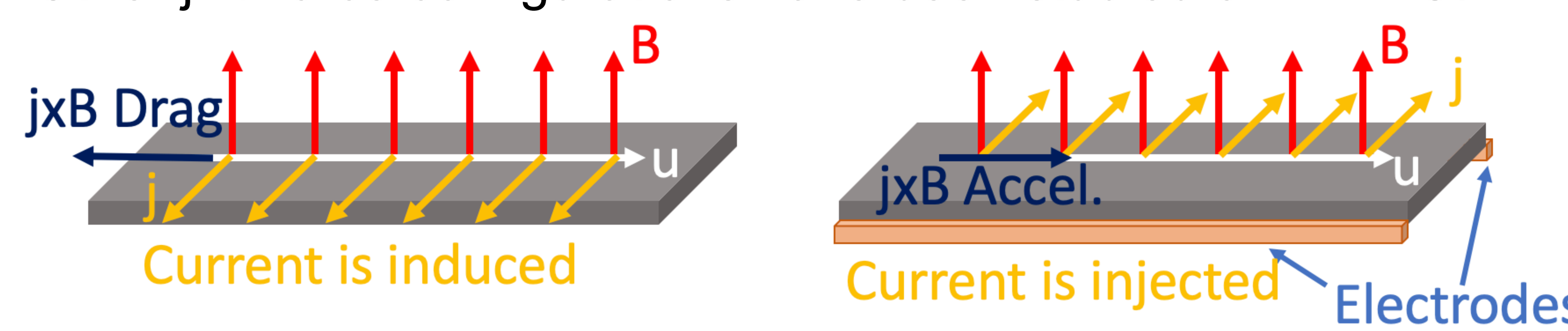

Figure 5. Example of how MHD drag (jxB drag) can be opposed using externally injected electrical currents.

In order to implement such a setup in a divertor, the divertor will likely have to be broken up into cassettes. Each cassette would then have electrodes on either side, and pass current across the flow to create a propulsion force. In Figure 6, magnetic field is directed into the page, creating a jxB force directed radially outwards.

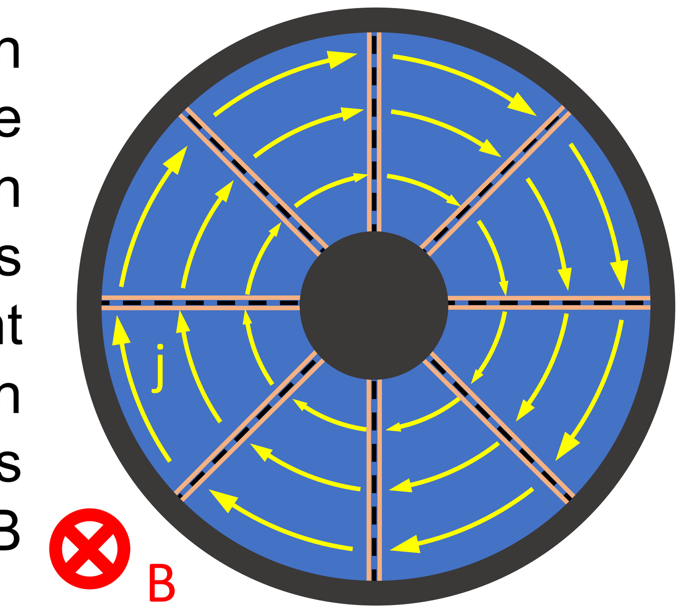

Figure 6. Sample cassette arrangement, j is clockwise

Experimental Setup

The Kyoto University LMFREX channel was placed below the Oroshhi-2 superconducting magnet in a region of approx. 40% field strength compared to the core (shown in Figure 3). An array of mirrors was used to gain optical access to the channel to implement a laser sheet and camera diagnostic. The graphic below shows an approximate representation of the setup.

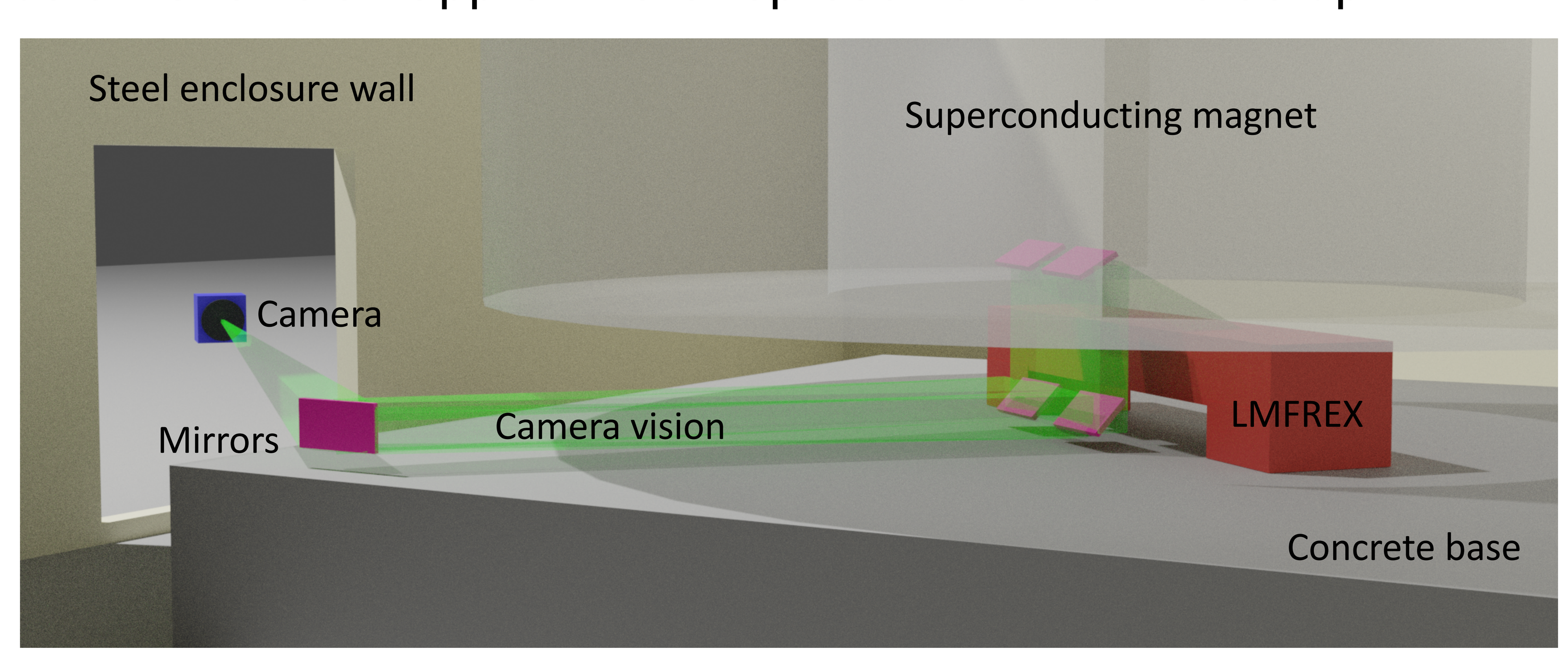

Figure 7. Experimental setup showing camera and mirror array—The laser sheet used separate mirrors and shined vertically down

Results

MHD thrust was successfully used to accelerate the free-surface flow. Hydraulic jump was observed, showing the need for countermeasures in a reactor [3]. Figure 8 shows an image taken from the channel, along with the processed depth in Figure 9. Data from multiple test cases are compiled and plotted in Figure 10. With modest currents (<150 Amps) appreciable flow acceleration was seen—current can be increased for further acceleration.

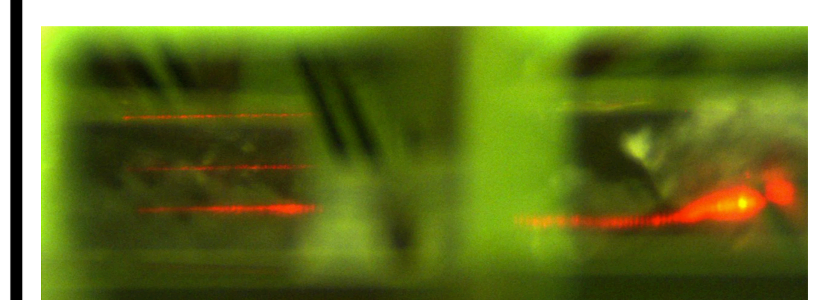

Figure 8. Still of LMFREX video showing flow left to right with a hydraulic jump forming on the right

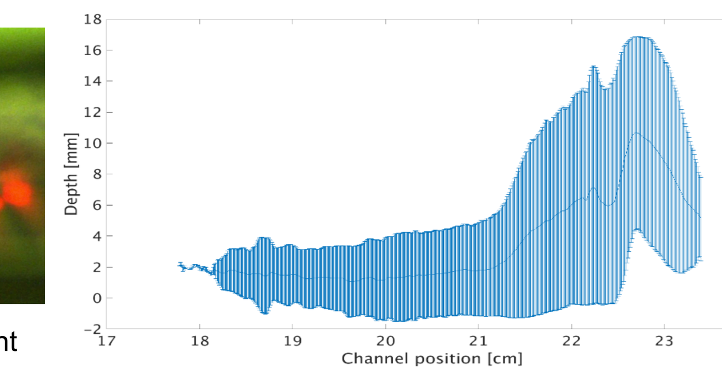

Figure 9. Processed depth data from still on the left

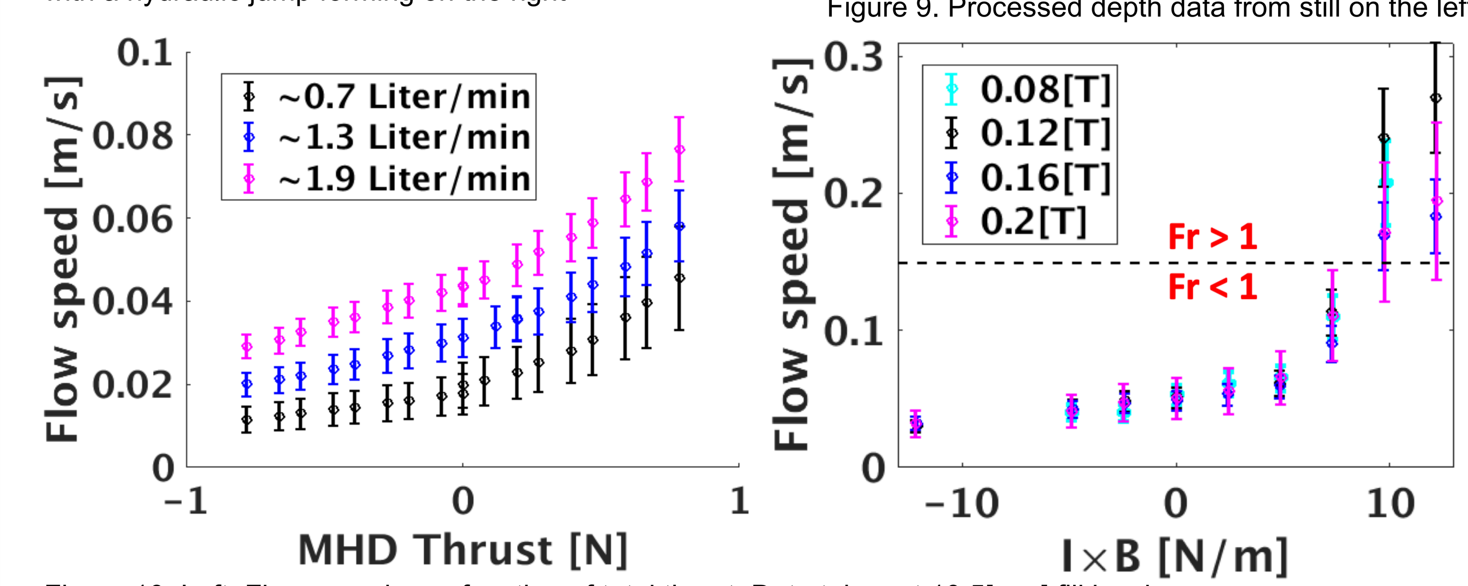

Figure 10. Left: Flow speed as a function of total thrust. Data taken at 10.5[mm] fill level
Right: Flow speed as a function of thrust per-unit-width. Data taken at 6[mm] fill level—Fr>1 caused hydraulic jump

Future Work

The Liquid Metal eXperiment Upgrade (LMX-U) at PPPL is being re-engineered for higher magnetic field and field angle control—mimicking conditions at a divertor. Wall electrodes will be used with the vertical B component for MHD thrust.

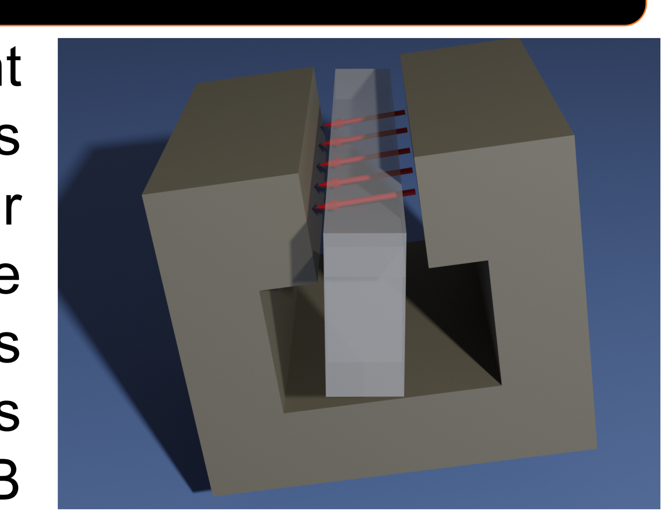

Figure 11. LMX-U magnet at an angle—the red arrows represent magnetic field vectors

References

[1] R. Majeski, et. al., 2016
[2] Oroshhi-2, NIFS, Toki, Japan
[3] A. E. Fisher, et. al., 2018