Introduction:

Flowing liquid metal is an attractive solution to many of the problems faced by solid metal plasma facing components in fusion reactors. Amongst the benefits are having higher heat flux capacities, self-healing properties, and enhanced power extraction. The idea for flowing liquid metal walls has existed for several decades; wall restraint methods include using inertial and/or electromagnetic forces. Speed and thickness of the wall has evolved over time due to different engineering concerns; the type of flowing wall design I plan to research is electromagnetically constrained, thin film (~1-2 cm) high-speed (~10 m/s) flow. Fast-flowing liquid metal is able to serve both as surface protection and handle all heat removal, keeping the outer solid wall cool enough that it can be made of materials with relatively low melting points such as steel rather than the traditional materials with very high melting points like tungsten.

Challenges faced for this flowing liquid metal wall design are among but not limited to: splashing, hydraulic jump and surface boiling. The primary goal of my thesis is to design diagnostics and control systems to detect and regulate these phenomena.

MHD flow is markedly more complex than flow predicted by standard Navier-Stokes. Conducting fluid motion and electric current interactions with magnetic fields result in complicated flow behavior due to the non-uniform body forces the flow experiences. Flow control options are opened up with these forces, and it is important that they are researched so that they may be implemented into fusion reactors to improve performance.

There are also classic fluids problems to consider. Hydraulic jump has been investigated for over a century, but the intricacies of its cause and time evolution are not completely understood. While a hydraulic jump may be observed in a sink from water rushing radially outwards, the exact conditions that initially cause the hydraulic jump to begin aren't obvious. In a reactor setting it is unknown if the MHD drag or reactor wall roughness are large enough to trigger a jump, for if a jump does occur the thin fast flow will become a thick slow flow.

Research conducted thus far:

The machine I have been working on is LMX, a liquid metal (galinstan, a eutectic alloy of gallium indium and tin) channel flow in a magnetic field that can have external currents injected through the liquid metal. The first objectives for LMX were characterizing the system—specifically determining the magnetic field profile in the channel and the pump performance. This was accomplished using a gauss meter and flow meter respectively, and the calibration results were used for future experiments.

Vertical heat transfer was one of my first investigations. The bottom of the flow channel has an array of thermocouples installed to report the temperature of the liquid metal. In addition, there is an infrared camera installed to look at the surface. To heat up the flow a small, rectangular ceramic heater is installed touching the top of the flow. By operating at the same heater power and varying magnetic field strength and external current amplitude, we measured the vertical heat transfer. The height of the flow in the channel, i.e. the bulk flow variation as a function of Lorentz force had a dominant impact on the heater-LM contact compared to the heat flux variation. To overcome this issue, I designed a floating heater system that we are preparing for installation this year.

The infrared camera that looks at the surface of the liquid metal flow has difficulties in determining the galinstan surface temperature because of how low the emissivity is. This property was used to our advantage, as oxidized galinstan has a relatively high emissivity and small traces appear quite clearly to the camera while a traditional camera would have difficulties in distinguishing the two due to their similar visual appearance—especially in a low-light environment. With these results, I authored a paper showing how an infrared camera can track surface velocity of a liquid metal where other established methods would fail.

Most recently, I have been working on a paper that quantifies the height change seen when applying a vertically directed Lorentz force. By using mass and momentum conservation and treating Lorentz force as an added body force like gravity, the height changes seen in the experiment were fit nicely to theory. Theoretical calculations were done by adding the effective acceleration due to Lorentz force to gravity in the relevant equations—typically the magnitude of the Lorentz force used in the experiments was between 1 m/s^2 and 6 m/s^2. The experimental data was collected using a laser sheet diagnostic that I installed. This diagnostic uses a HeNe laser with a cylindrical lens installed at the tip aimed vertically downwards at the liquid metal. The cylindrical lens causes the laser dot to be turned into a line, a camera then tracks this line and its position can be converted to millimeters using calibration fits.

Planned research:
LMX is currently being upgraded to achieve higher flow speeds, specifically to attain flows that exceed Froude number equal to one. Hydraulic jump control is the first planned experiment following the upgrade. A flow condition that would normally jump should be able to be replicated with an added Lorentz force so that it will no longer jump due to effective increase in gravity—then lowering the Froude number to below one. While doing initial calculations with the relevant equations to create a test matrix, I came across some strange flow conditions that will be interesting to observe in experiments in the coming months.

Following LMX I will be working on FLiT (Flowing Liquid Metal Torus) which is planned to be a toroidally flowing liquid metal wall with reactor-relevant flow speeds and magnetic fields. Many of the LMX findings are being used in the design process for FLiT, with the upgrades on LMX planned to further explore nozzle designs and the most probable causes of hydraulic jump. While I won’t be heavily involved in FLiT’s construction, I’ve been giving input for the final design and will be developing and installing liquid metal diagnostics when the device is built.

Simulations using COMSOL are useful tools for the current experiments on LMX to help predict and explain what is happening at different flow conditions. I have begun to perform some of these simulations myself, and the future simulations for FLiT will be integral in the design process. Some of the most recent quantities of interest are the pressure drop expected across the MHD pump we’re designing and the extent of the MHD drag on the flow inside the magnetic field.