Development of a Non-Contact, Inductive Depth Sensor for Free-Surface, Liquid-Metal

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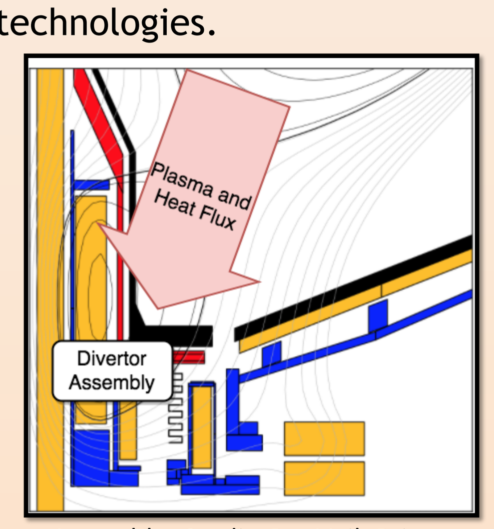
GOALS

- **Create a device that can accurately measure galinstan depths without being immersed in the liquid metal.**
- **Measure thickness of galinstan through stainless steel substrate.**
- **Use freely available software to simulate and calibrate experimental results.**

BACKGROUND

Liquid Metal Divertors

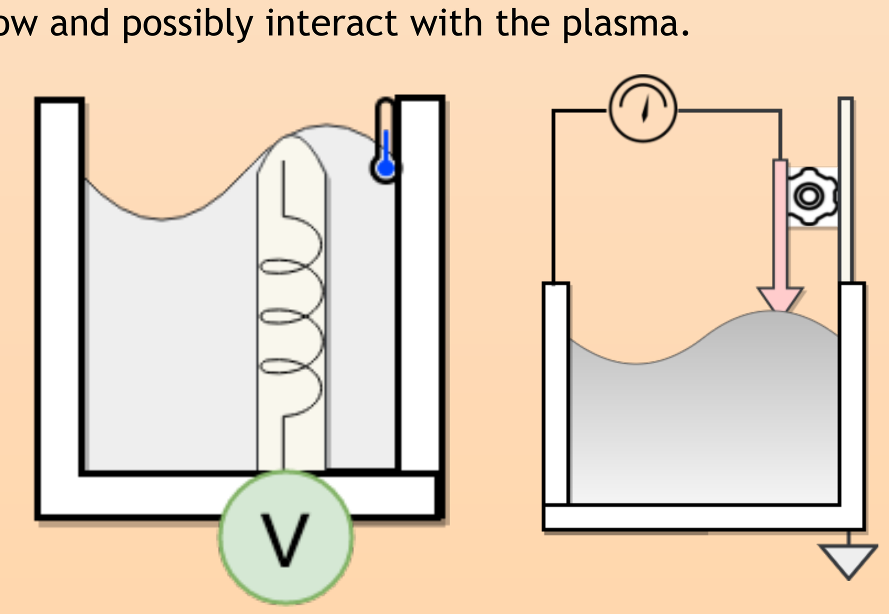
- Future nuclear fusion reactors will have to contend with enormous heat loads (>10 MW/m^2) and plasma fluxes on plasma facing materials, especially the divertor.
- A fast flowing liquid metal is one type of plasma facing material being investigated.
- Liquid metal is immune to radiation damage and thermal stress.
- PPPL is involved with developing and advancing liquid metal plasma facing technologies.



NSTX Divertor Assembly, Credit: Pat Vail, Princeton University

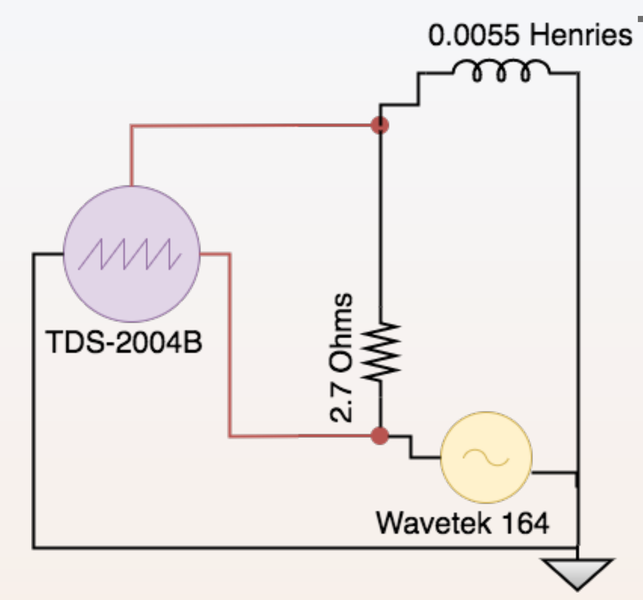
Liquid Metal Depth Sensors

- There is a large amount of experience with liquid metal in closed channel flows from liquid metal fast fission reactors[4].
- All of these systems use sensors that are in direct contact with the liquid metal, or have complex external systems that do not lend themselves very easily to nuclear fusion reactor environments.
- Fast flowing liquid metal plasma facing components will need sensors that are non-contact, so as to not interfere with the flow and possibly interact with the plasma.



Inductive Probe and Contact Probe Liquid Metal Depth Sensor

EXPERIMENTAL METHODS



L-R Circuit Diagram for Liquid Metal Depth Sensor

Inductor-Resistor Circuit

- The sensor was built from a coil put in series with a resistor to form a small L-R circuit.
- The coil voltage and power supply voltage were measured and subtracted to calculate the resistor voltage.
- The coil and resistor voltages can be used to calculate the inductance of the coil[1].

L = Inductance of coil (H), V_c = Voltage of circuit (V), V_R = voltage of resistor ((V) R_r = resistance of resistor (Ω), R_l = resistance of coil (Ω), f = frequency (Hz)

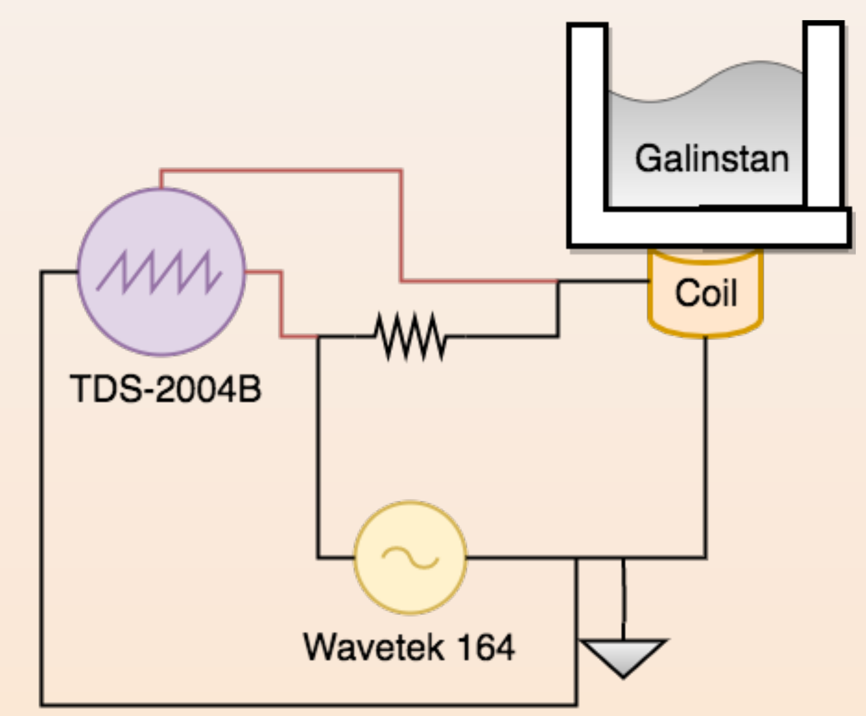
$$L = \frac{\sqrt{\left(\frac{V_c R_r}{V_r}\right)^2 - R_r^2 - R_l^2}}{2\pi f}$$

Galinstan Height Measurements

- Conducting material brought near a coil will change the total inductance of the coil.
- The amount of material present, the materials conductivity, the relative permeability of the material, and the frequency of the coil determine the amount and direction of the inductance change.
- Too high of a frequency will not penetrate the entire depth of the conductive material and will not allow for a complete depth measurement due to a phenomenon known as the skin depth effect[3].
- Galinstan is has a conductivity of 2.3-3.1(MS/meter) and a μ_r less than one. Thus it will decrease the inductance and has a skin depth of 1.2 (cm) at 510 (Hz).

$$d_s = \sqrt{\frac{\rho}{\pi f \mu_r \mu_0}}$$

d_s = skin depth (cm), ρ = bulk resistivity (Ω-m), μ_r = relative magnetic permeability, μ_0 = magnetic permeability constant (H/m), f = frequency (Hz)

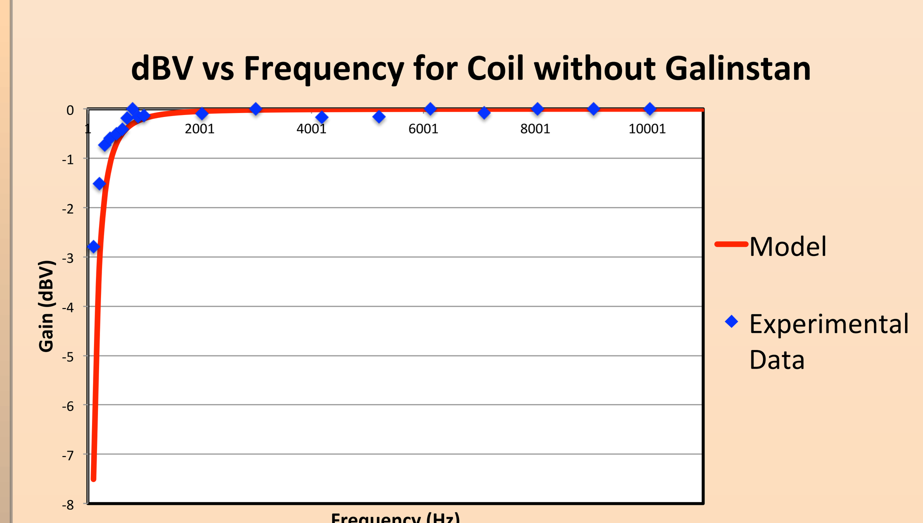


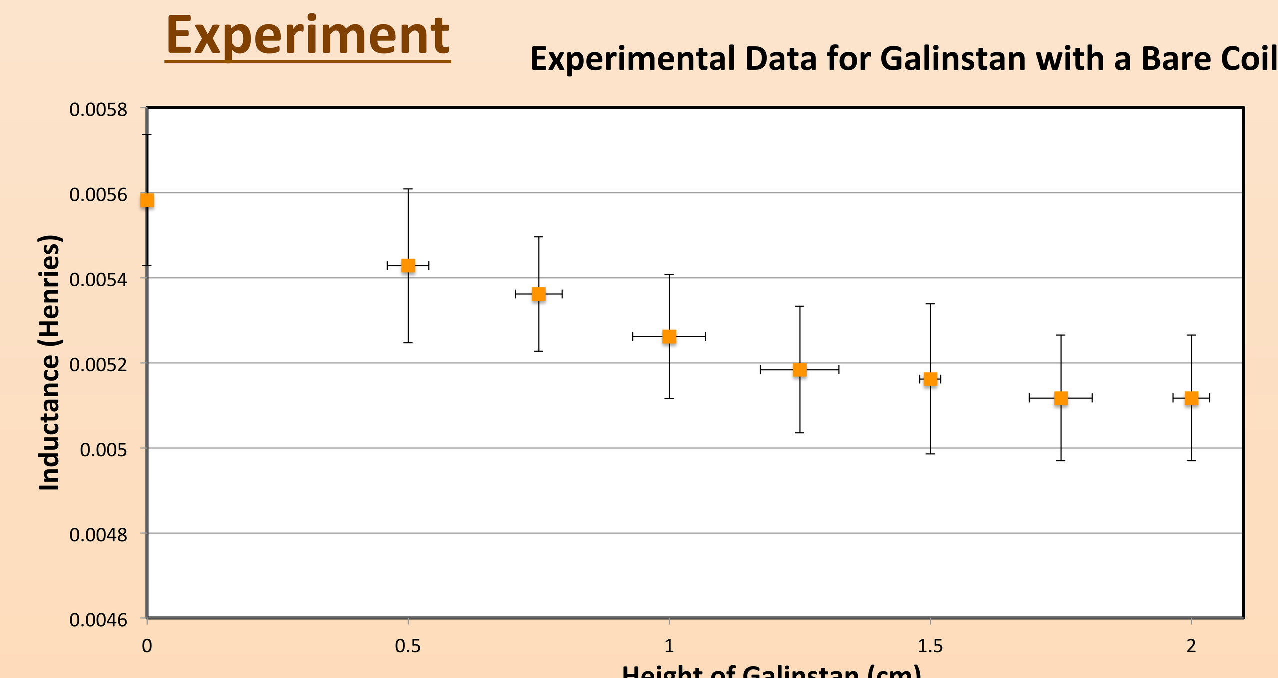
Liquid Metal Depth Measurement Experiment Setup

- Inductances were measured with different galinstan heights and compared to a finite element analysis software called Finite Element Method Magnetics[2] (FEMM).
- Inductance measurements were also taken with 1/16", 1/8", and 1/4" stainless steel placed over the coil and compared to FEMM results.

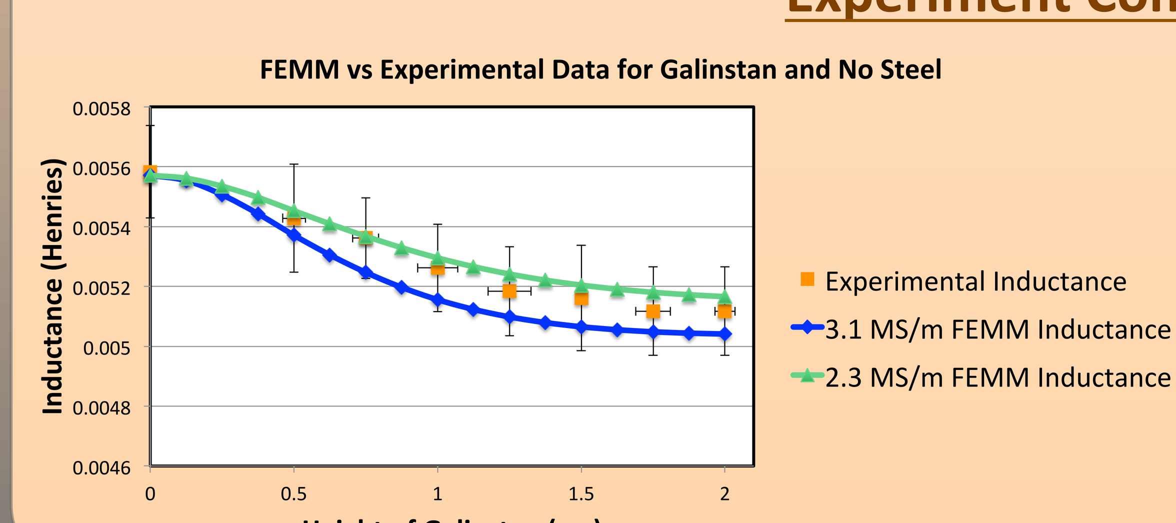
Results

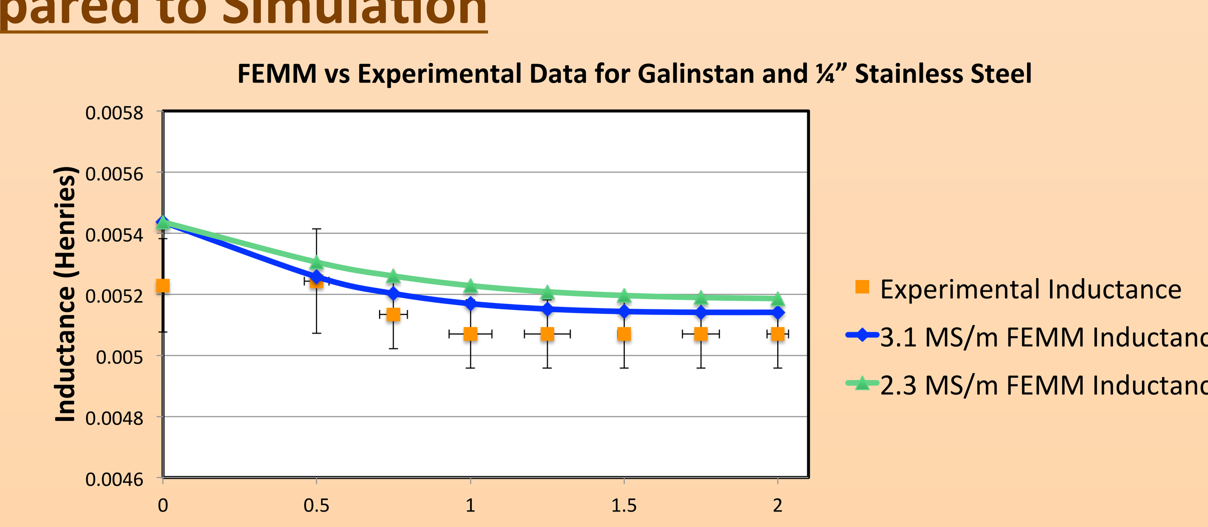
Experiment



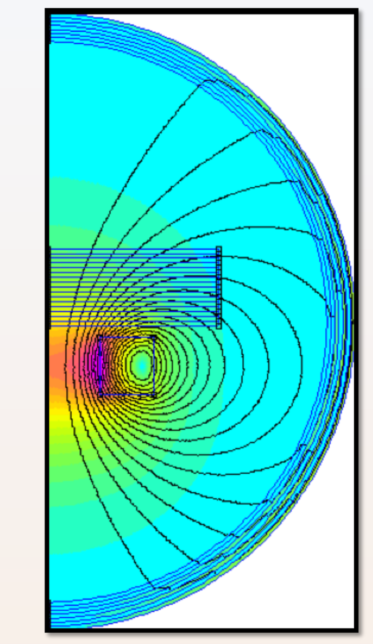


Experiment Compared to Simulation

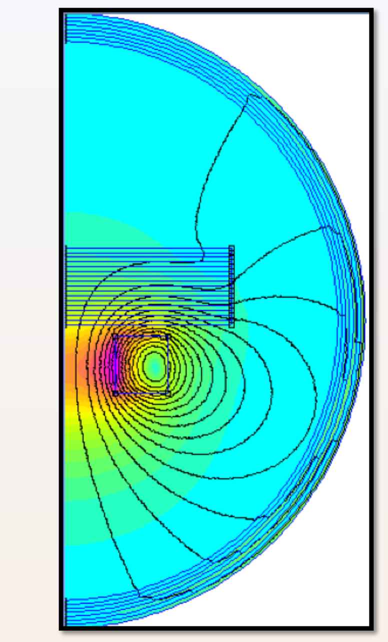




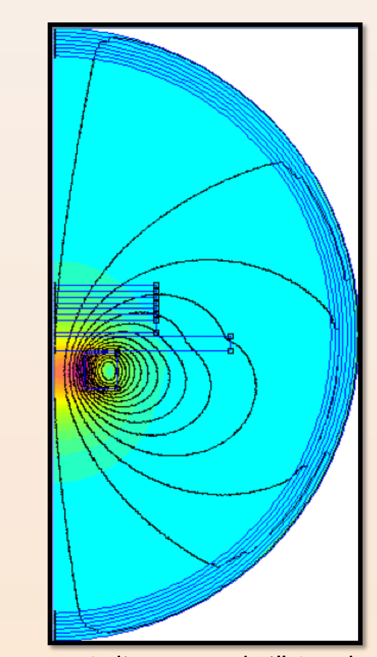
Simulation Output



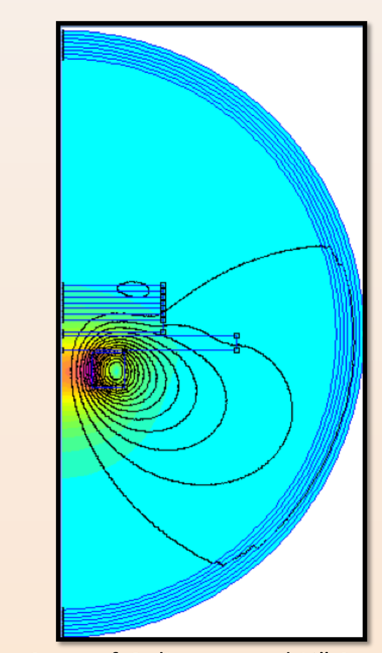
No Galinstan and No Steel



2 cm of Galinstan and No Steel



No Galinstan and ¼" Steel



2 cm of Galinstan and ¼" Steel

CONCLUSIONS

- A non-contact liquid metal depth sensor with an accuracy of roughly 1-mm was demonstrated and calibrated with a FEMM simulation for a bare coil.
- Liquid metal presence and depths were detected through layers of steel, but the simulation did not match the data well enough due to unknown properties of the school..
- Further simulation refinement and more accurate measurements will allow for detection and calibration through layers of steel.

Future Work

- Further characterization of sensor with steel placed between the coil and the galinstan will need to be done.
- An investigation into the effects of different temperature galinstan along with more accurate conductivity measurements will be needed for more accurate models.
- An investigation into the response of the sensor to waves in the galinstan, so as to better understand how fast flowing liquid metal will be detected.
- A full integration of the sensor into an active liquid metal test apparatus for final debugging.

Acknowledgments

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