Safety and diagnostic systems on the Liquid Lithium Test Stand (LLTS)

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? Motivation

- Liquid lithium is a PFC candidate material.
- Eventually flow liquid **Li** in NSTX [1].
- Difficult to handle: hot, ignites in air, very reactive.
- Not many facilities with flowing **Li** exist.
- Demonstrate safe and reliable operation at PPPL.
- Test flowing free-surface components under vacuum.

Ω Overview

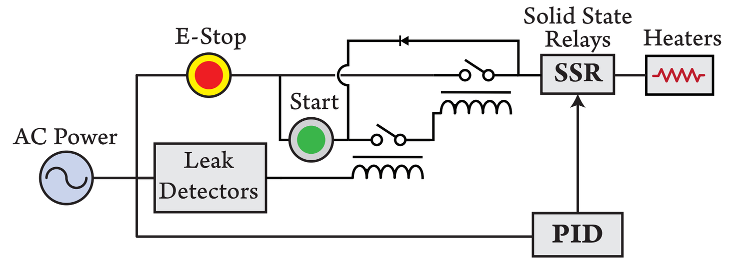
- A flowing liquid lithium system at PPPL currently under construction.
- Goal of demonstrating pumping, freezing, and reliquefying while under vacuum.
- Loop consists of two resevoirs and a pump, in a stainless steel enclosure.
- Roughing pump and turbopump for vacuum.
- Few L/min flow rate.
- Nominal max temp 500˚C.
- Diagnostics include thermocouples, vacuum pressure (Pirani) gauge, magnetic flowmeter.
- Heaters and motor interlocked with a leak detection system.
- Goal to be `walk-away safe'.

→ Future work

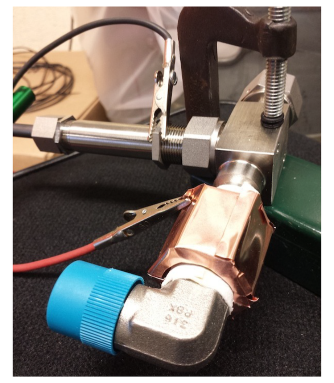
- Complete structure and diagnostics assembly
- Characterize loop operation
- Add chamber for testing flowing free-surface lithium PFC designs

1 Leak-detecting interlock

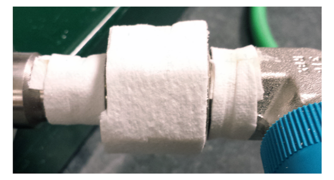
- Shuts off power to heaters and pump motor in the event of a leak.
- Monitors conductivity between a copper shell around each joint and ground: normally an open circuit, a liquid metal leak will close the circuit.
- Digital output is recorded by computer through an NI DAQ card as a log.
- Latching relay system keeps heaters and pump off after a fault until operator hits `Start' button.



Latching relay system for interlock circuits.

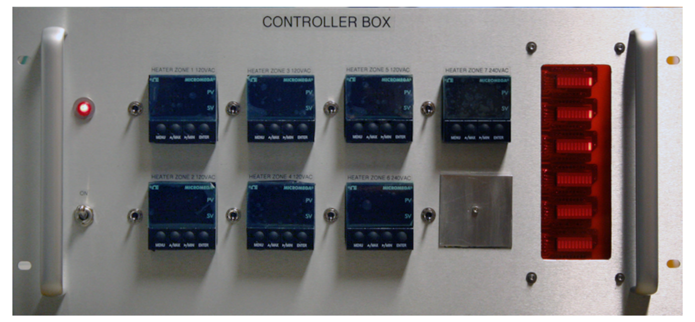


A copper shell surrounds a VCR fitting joint. If there is resistance R < 2kΩ between the shell and the pipe the interlock is triggered, shutting off power to the heaters and pump.

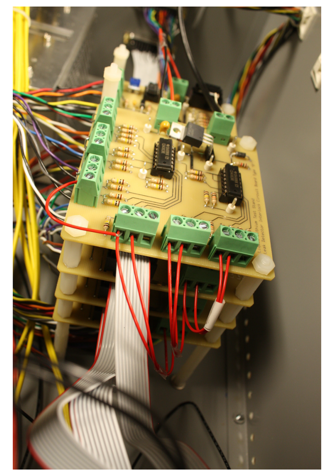


The copper shell is stood off from the pipe by insulating ceramic tape.

- LEDs on the front panel and latching indicators in LabVIEW allow easy fault locating. This discourages bypassing the interlock system.
- Up to 24 channels, expandable to 48.
- Could also be used to interlock enclosure doors.



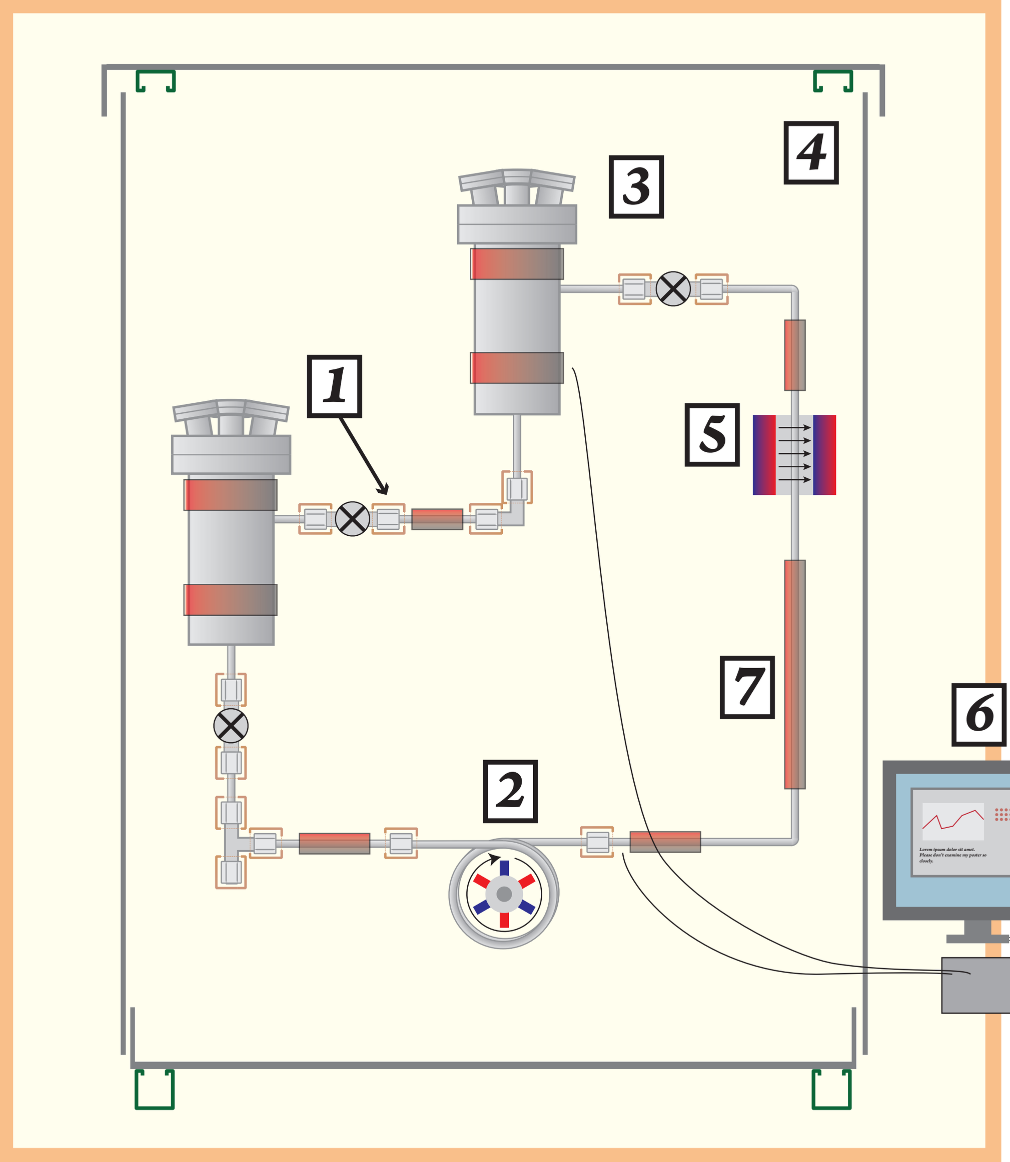
Front panel for the interlock circuit (at right). The 3 lit LEDs signify that there are 3 powered input boards (of 8 channels each). A fault will light the LED corresponding to its channel and register in LabVIEW for easy fault locating, discouraging bypassing of the interlock. Heater controllers (off) are at center.



Stack of four boards handles up to 24 interlock channels. Top board can support up to three more input boards for 48 channels.

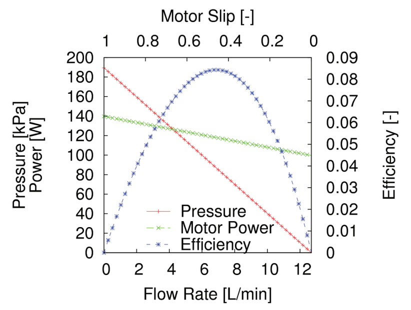
Scenario	Immediate result	Safes?
Power to interlock circuit is shut off	Heaters and pump power latch off	Yes
Cable between interlock circuit and power distribution box is removed	Heaters and pump power latch off	Yes
Lithium leaks from a pipe joint	Heaters and pump power latch off	Yes
Mechanical forces cause contact between copper shell and the pipe.	Heaters and pump power latch off	Yes
Operator pushes E-Stop button	Heaters and pump power latch off	Yes
Copper shell touches pipe, interlock triggers and shuts off power to heaters and pump. While they are still in contact, operator pushes START button.	System cannot be started when the leak-detector interlock is still triggered.	Yes
Wires leading to one leak-detector shell are cut or detached	That interlock channel is no longer functional.	No

Table describing fault scenarios for the interlock circuit.

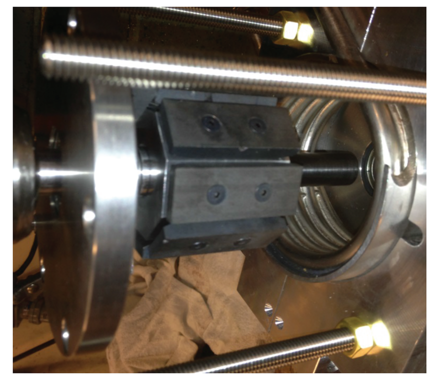


2 Liquid metal EM pump

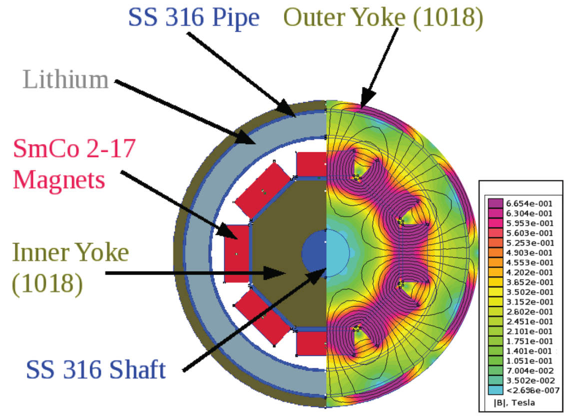
- No moving parts contacting fluid, no break in pipe integrity.
- Novel use of rotating magnet pump with **Li**.
- Magnetic field drags conducting fluid. Based on designs by Bucenieks [2].
- The ½ hp motor's shaft is on the axis of a 5-turn solenoid of pipe.
- High-temp (>400˚C) SmCo magnets mounted with poles facing radially.
- Control system pressure and flow rate by adjusting motor speed - up to 1000s of RPM.



Predicted motor characteristics.



Motor during assembly. 5-turn solenoid of pipe is to the right, magnets are center.



Construction of pump and simulated magnetic field strength.

3 Material Compatibility

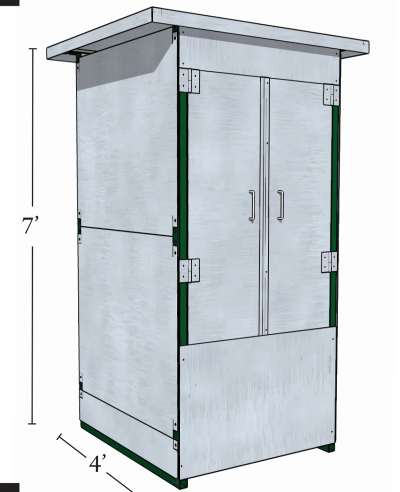
Liquid **Li** is compatible with **W**, **Mo,** some Stainless Steels (304, 316) but not with **Cu**, **Al**, concrete, air or $\mathbf{H_2O}$.

- Tube is 316 Stainless Steel.
- Joints are VCR fittings with stainless steel, not-silver-coated gasket seals: less permanent than welding.
- Conflat flange gaskets are a heat-treated (to soften) 1008 steel instead of standard **Cu**.

Conflat Gasket Vacuum Test:
After 24 hours,
Cu: 9×10^{-7} Torr
Steel: 6×10^{-7} Torr

Conclusion:
Steel works just as well.

4 Steel enclosure

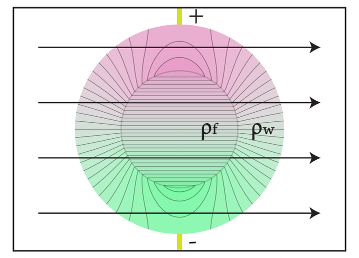


- Still need fire protection in regular lab spaces.
- **Li** reacts with water and concrete floor.
- Protects from showers of water (from fire sprinklers) and from a spill touching the concrete floor.
- Put entire loop inside a 304 Stainless Steel enclosure.
- Sheet metal and strut channel: easy to build.
- Base plate 1/8" thick, sides 0.030" and 0.024"
- A 3rd level of containment after pipes and copper shells around joints.

5 Magnetic flowmeter

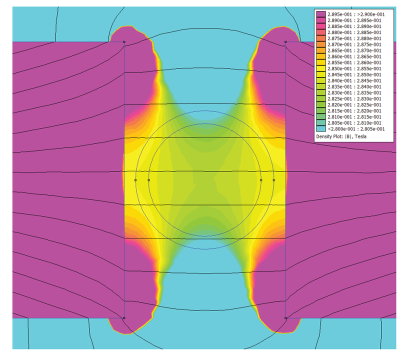
- Measure flow without moving parts.
- MHD effect: $\phi \sim B\,d\,v$
- For azimuthally symmetric flow, measured voltage depends only on average velocity [3].

$$\phi = \frac{Bd\bar{v}}{\frac{D^2+d^2}{2dD} + \frac{\rho_f}{\rho_w}\frac{D^2-d^2}{2dD}}$$

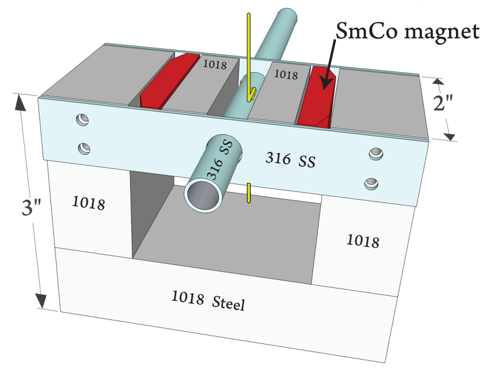


Contours of voltage for slug flow and $\rho_w = \rho_f$, D = 2d.

- With B~0.22 T, D=3/8", flow rate ~ 1 L/min, expect ϕ around $5 \cdot 10^{-4}$ V
- Built from same high-temperature SmCo magnets as motor; 1018 steel yoke.



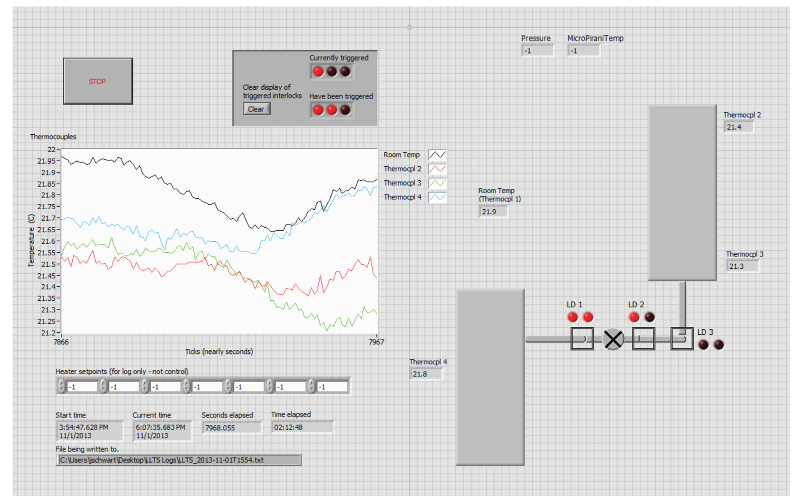
Field from FEMM uniform to within ~2%. Predicted |B| of ~0.28 T, measured ~0.22 T



Flowmeter construction. Voltage pickup wires will be welded to top and bottom of the pipe.

6 External monitor and log

- A LabVIEW program monitors and logs to disk readings from thermocouples, vacuum system pressure, and each leak detector channel.
- Determine at a glance where a leak (or other fault that tripped the interlock circuit) occurred, even for intermittent faults: Digital lines from the interlock circuit are polled at 1kHz, ensuring that intermittent faults are recorded.
- Thermocouple readings are displayed on the chart and at their location on a diagram of LLTS.
- Monitor cooldown to determine when device is no longer too hot to touch.



Example front-panel display for logging program. Notable are the pairs of lights for each leak-detector circuit: One light shows whether the circuit currently has a fault, and one shows whether it ever had a fault.

7 Multiple Heater Zones

- Seven independently adjustable heater zones
- Reduce thermal stresses by keeping uniform temperature during ramps - prevent thermal shock.
- Nominal max temperature 500˚C.
- Less than 10 kW of heater power with use of high-temperature insulation.
- Heater PID controllers receive feedback via thermocouples.
- All heater power will shut off if leak-detector interlock is triggered, but heater controllers remain on.

& References

[1] NSTX Upgrade Five Year Plan
[2] I. Bucenieks, Presentation at IV Int. Workshop on Materials for HLM-cooled Reactors, Roma, Italy 2007.
[3] E. R. Astley , *Magnetic Flowmeter Output Potentials,* (G.E. R52GL42), March, 1952.

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