Lithium Experimental Application Platform (LEAP)

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Content

- Need of large-scale lithium experimental platform
- Development of LEAP
- LEAP as an interface to fusion facilities

PPPL's mission & alignment with DOE's strategic goals

Mission 1 — Developing the scientific knowledge and advanced engineering to enable fusion to power the U.S. and the world

- Optimizing the magnetic confinement system
  Spherical torus
- Developing models and measurements to predict, optimize and control fusion
  AI/ML; High-performance computing
- Taming interactions between the plasma and the reactor walls
  Liquid metals

  Fusion Innovation Research Engine (FIRE) Collaboratives
- Designing superconducting magnets that can withstand years of use
  Engineering

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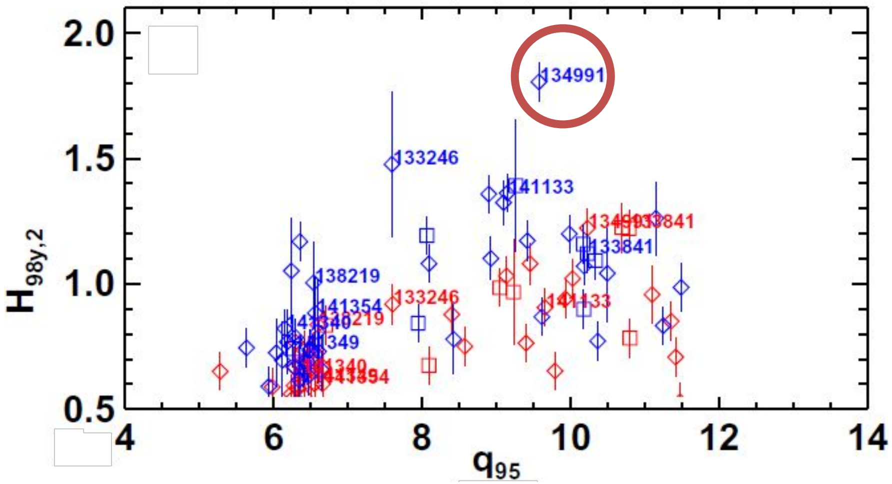
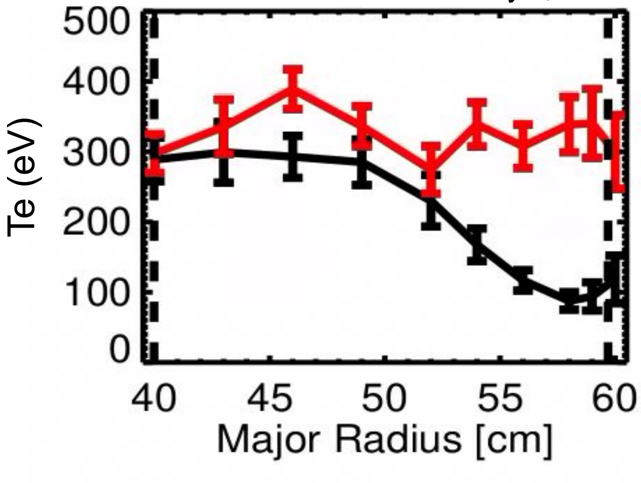
Plasma Control

Li coated wall increases confinement

Gerhardt et al. 2014 *NF*



Boyle, 2023



NSTX
Li enhanced pedestal H mode

LTX-β
Low recycling regime

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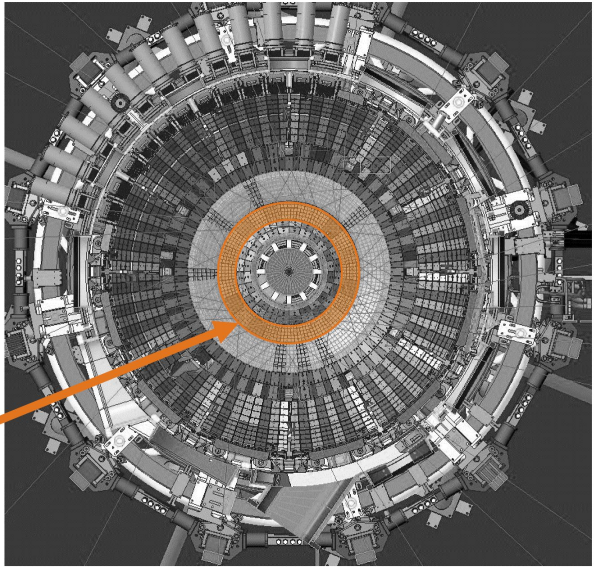
Liquid lithium as PFC

- Divertor, limiter, and alternative first wall material
  - Low-Z, getter impurities, low-recycling
  - Self-healing
  - Enhanced heat transfer

Khodak ANL 2023



NSTX-U Divertor region:
High magnetic field (B_T~1T);
High heat flux (~10-100MW/m^2)

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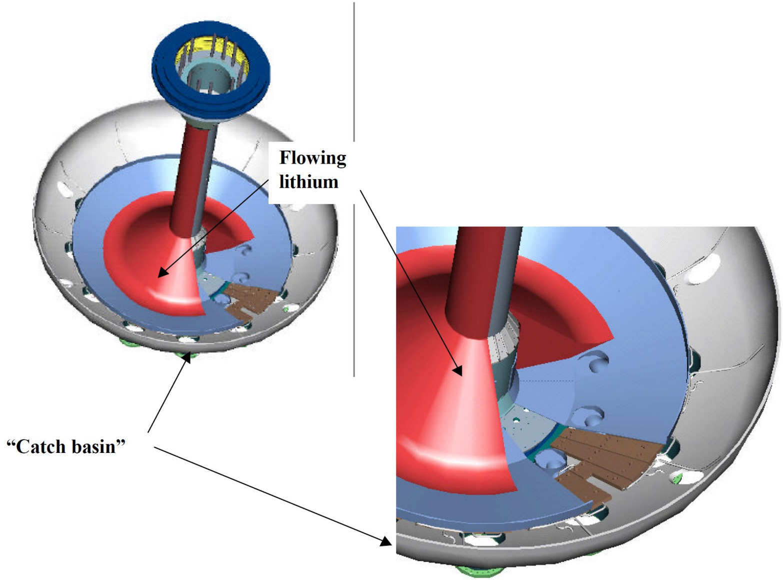
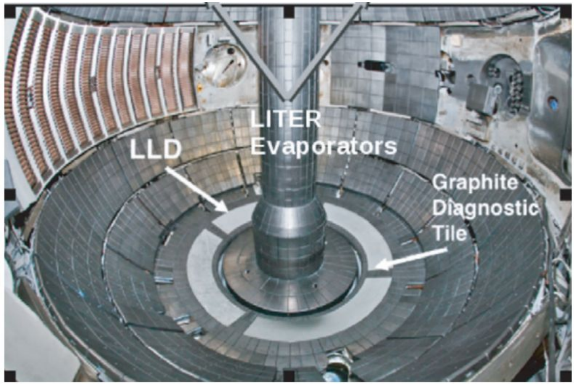
Liquid lithium as PFC

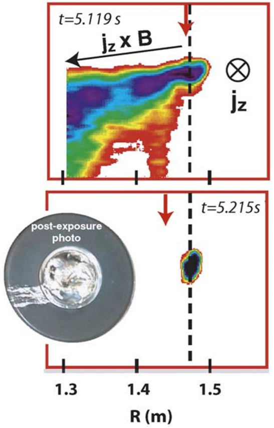
- Divertor, limiter, and alternative first wall material
  - Low-Z, getter impurities, low-recycling
  - Self-healing
  - Enhanced heat transfer
- Challenges
  - Fluid stability
  - Li/LiH circulation, plumbing
  - Alkali metal: safety, erosion



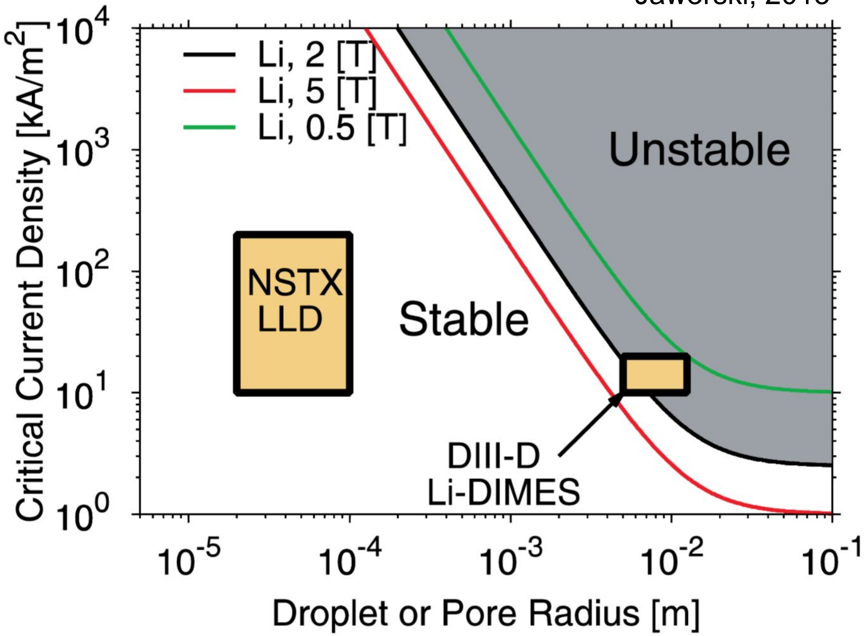
Kaita, 2000

Surface instability → droplet injection





Jaworski, 2013



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Surface instability → droplet injection

Growth rate

$$\omega = vk \pm \mathrm{i}\sqrt{\frac{\rho_{\mathrm{Li}} - \rho_{\mathrm{plas}}}{\rho_{\mathrm{Li}} + \rho_{\mathrm{plas}}} kg\cos(\theta) + \frac{f_{\mathrm{Li}}}{\rho_{\mathrm{Li}} + \rho_{\mathrm{plas}}} k - \frac{\gamma k^3}{\rho_{\mathrm{Li}} + \rho_{\mathrm{plas}}} + \frac{\rho_{\mathrm{Li}}\rho_{\mathrm{plas}}}{(\rho_{\mathrm{Li}} + \rho_{\mathrm{plas}})^2} (v_{\mathrm{Li}} - v_{\mathrm{plas}})^2 k^2} = 0$$

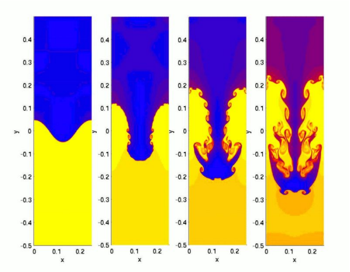
Gravity

Body force on Li (e.g., JXB)

R-T like

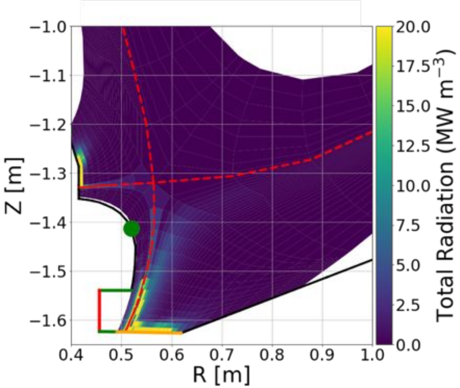
Stabilization due to surface tension

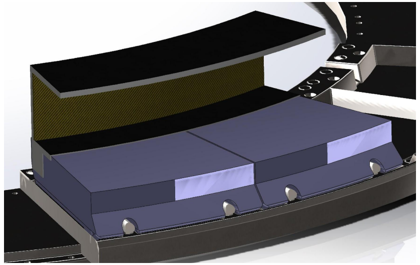
Destabilization due to K-H



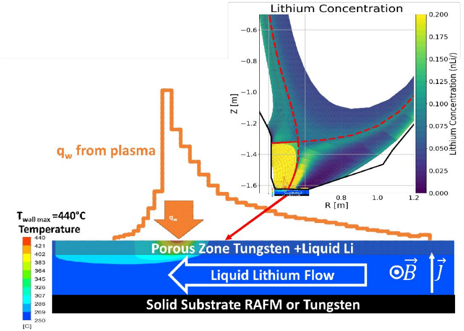
- Im(ω) > 0, the wave is unstable

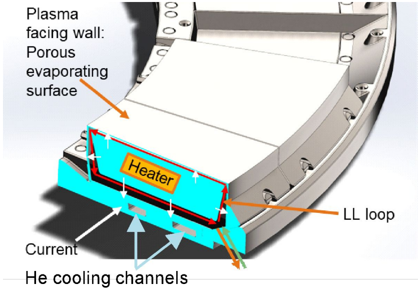
LMPFCs to be tested in NSTX-U/LMCE



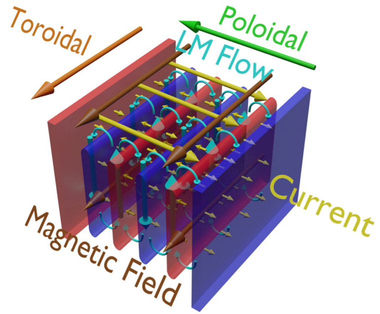


Simplified Li vapor box



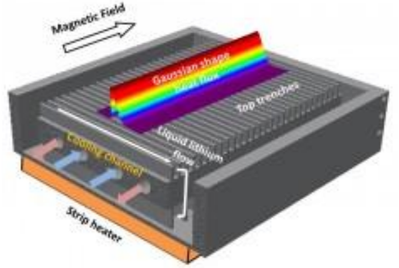


Capillary Porous System with Flow (CPSF)



Menard et al. 2024 LMCE whitepaper

Divertorlets: j×B flows Li in row of vertical cascades



Li-Metal Infused Trench (LiMIT)
TEMHD drives radial circulating flow

Liquid Lithium divertor designs → need subcomponent prototyping

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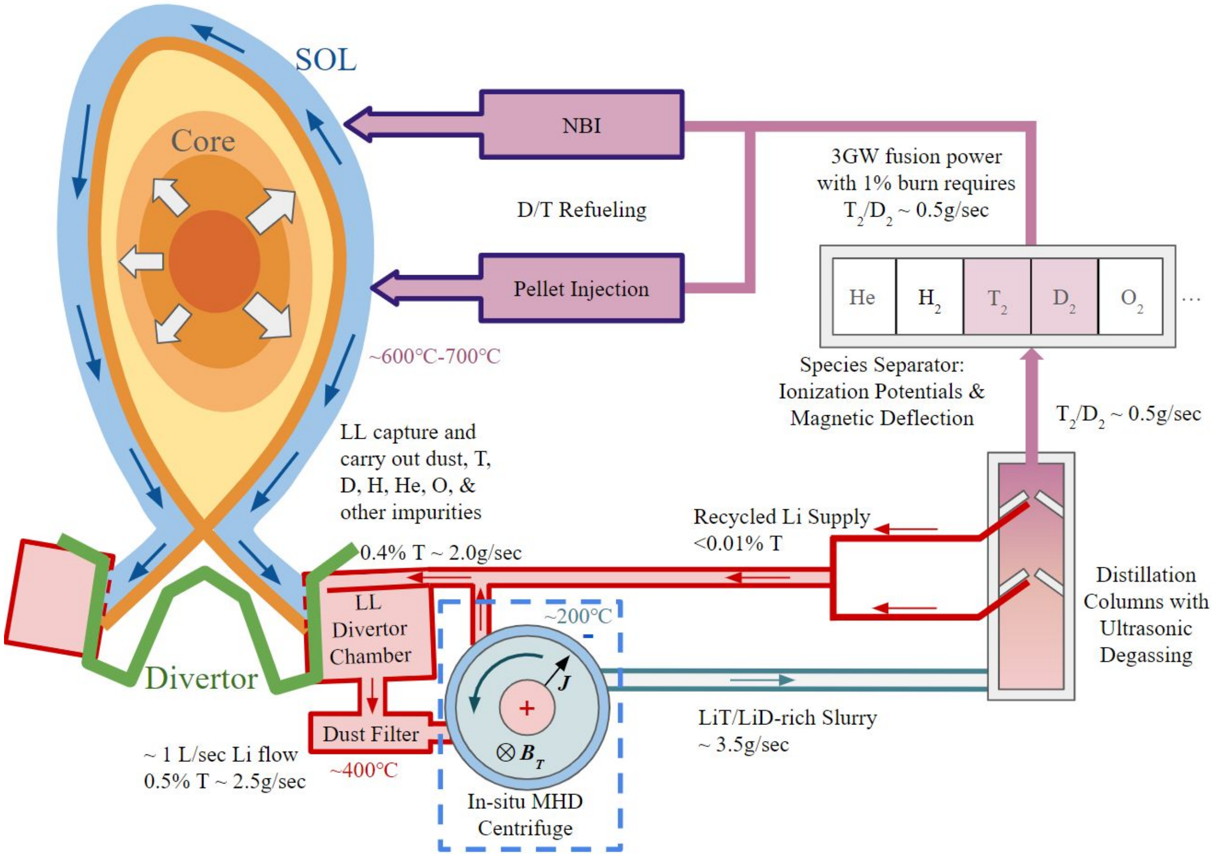
LMPFC challenge: Li/LiH circulation and transportation



- Fast flow designs ~1-10m/s
- Significant MHD drag
  - Insulating/magnetic field shielding piping
  - External current drive
- Li/LiH separation requires high volumetric flow rate ~1 L/s for tritium recycling (e.g., Ono et al. 2017).
- **Requires higher Li mass above current 5 lb inventory at PPPL's lithium labs.**

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LMPFC challenge: Lithium safety

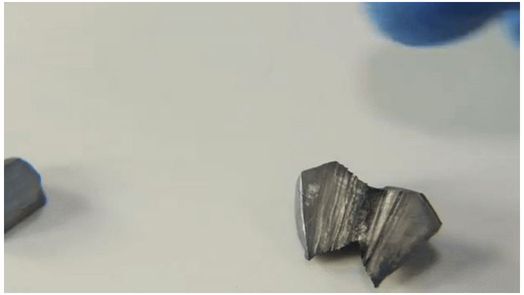
- Lithium is reactive with water and air
  $Li[s] + H_2O[g] = LiOH[s] + 1/2H_2$, $\Delta H_{298\ K} = -243$ kJ/mol
- $Li[s] + 1/6N_2[g] = 1/3Li_3N[s]$, $\Delta H_{298\ K} = -55$ kJ/mol

  This reaction is catalyzed by the presence of moisture in the air.
- $Li[s] + 1/2O_2[g] = 1/2Li_2O[s]$, $\Delta H_{298\ K} = -299$ kJ/mol

Lithium is incompatible with **moisture, oxygen, and nitrogen** (safety + impurity).

Ignition temperature in air varies from 180°C to 640°C depending on surrounding conditions. Reaction is sensitive to moisture and other impurities.

Solid lithium at room temperature is not pyrophoric, except for lithium powders. Molten lithium (180.50℃) is considered to be pyrophoric.



https://www.youtube.com/watch?v=5mvWQdad31o&t=3s

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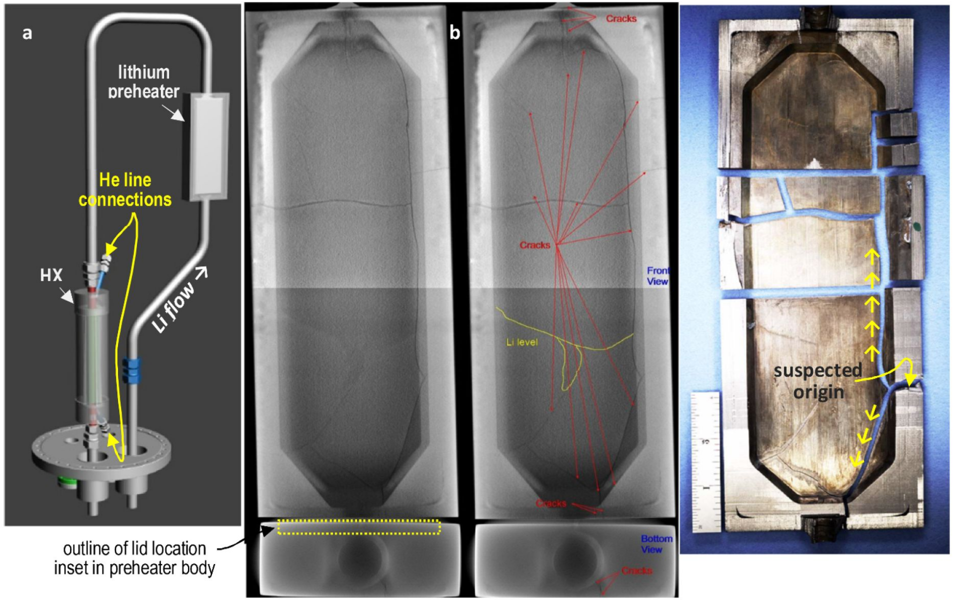
LMPFC challenge: Lithium safety

Nygren et al. 2021 *FED*

Sandia incident in 2011

Lithium-helium heat exchanger failure due to liquid metal embrittlement, liquid lithium sprayed abruptly onto a pipe holding the coolant → Hydrogen explosion.

- **Careful selection of materials to work with Lithium**
- **Robust system design to mitigate potential hazard**



A larger Li mass experimental platform is needed for LM PFCs Prototyping

Challenges:		Experimental platform design principle:
Prototyping different liquid lithium PFCs	→	Flexible, versatile
Fast-flow designs, tritium recycling	→	Large Lithium inventory (~50 lb)
Safety	→	Robust safety features and protocols

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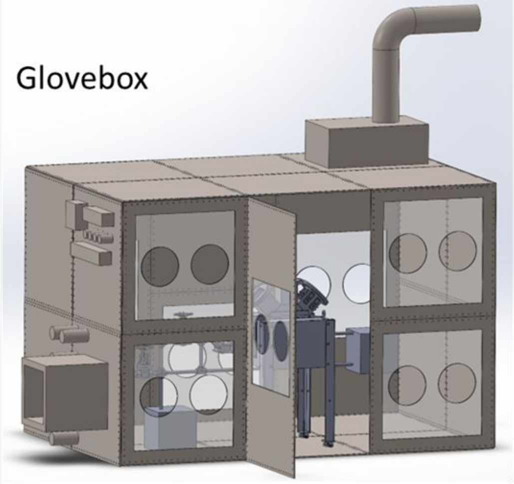
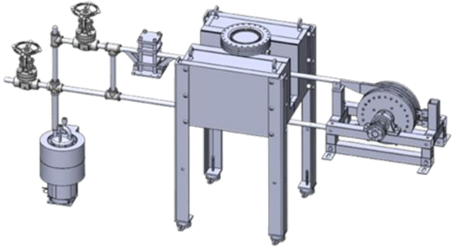
The Gloveroom Solution



Li Loop Apparatus



Manufacturer samples

- Testing full sectors of fast-flowing Li systems and LM PFCs with heat sources and B-fields. In planning phase. FDR for glovebox completed.
- Central component is (2m x 3m x 2m) prefabricated modularized glove box.
- Led by PPPL, designed to handle up to 50lb of liquid Li. Largest working liquid Li fusion experiment in US.
- Argon purging during operation (H_2O / O_2 level <1000 ppm) to ensure safety and inert environment.
- Equipped gloves and quick-open door for easy access and maintenance between operations.

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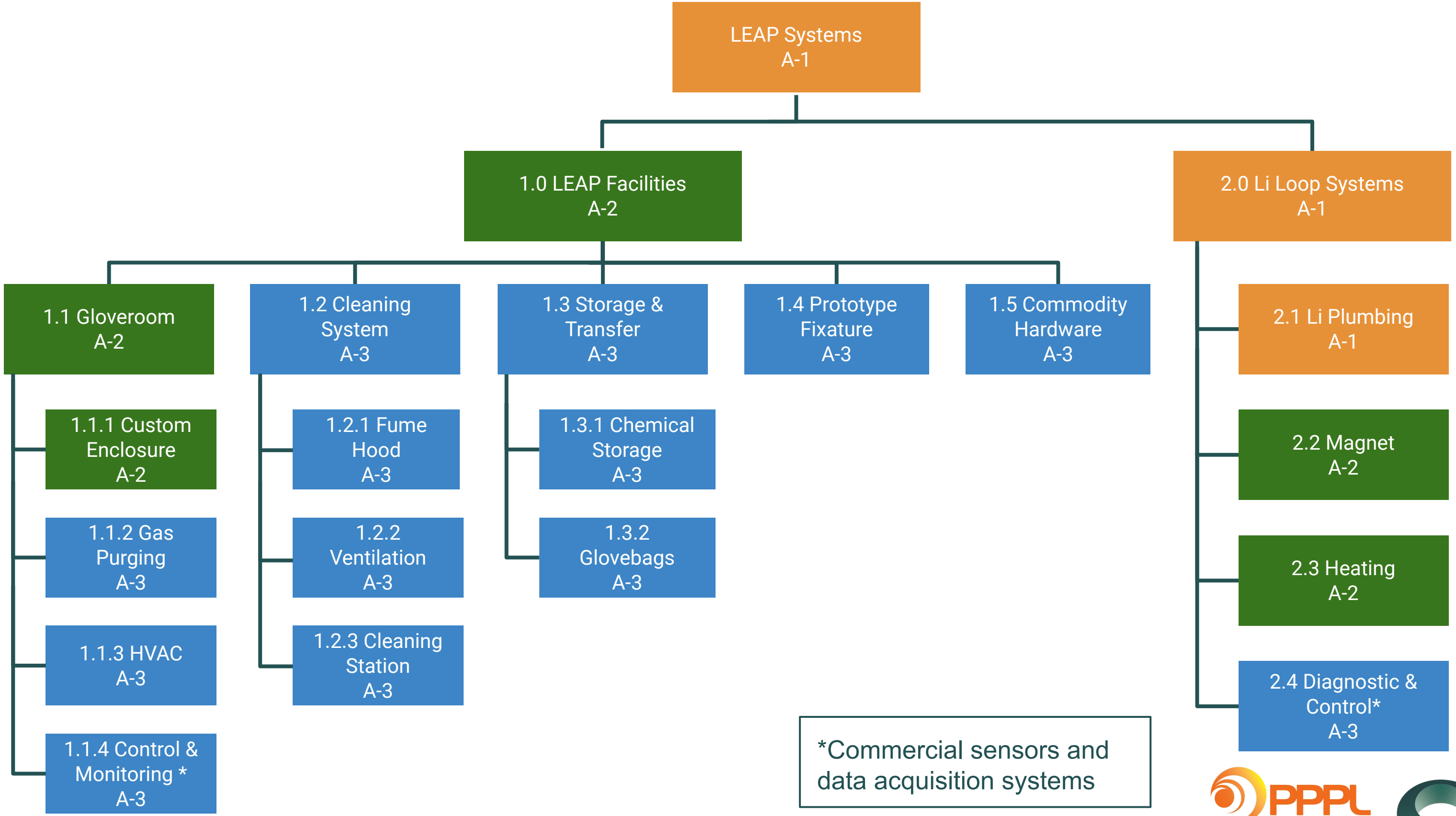
LEAP system



*Commercial sensors and data acquisition systems

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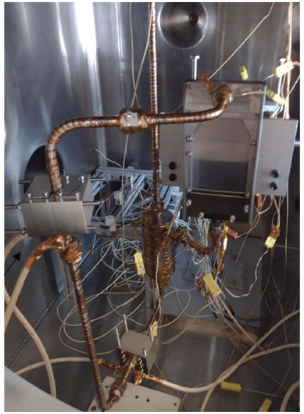
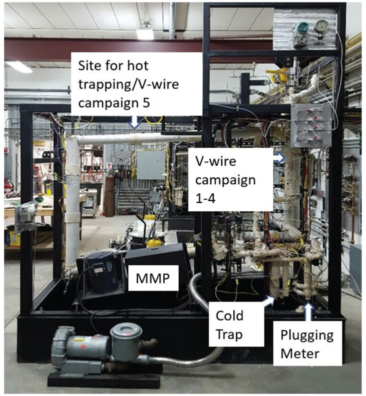
Design Choices & Comparison

UIUC, Li Loop in MEME



ANL, Sodium loop

UW-Madison, Sodium loop

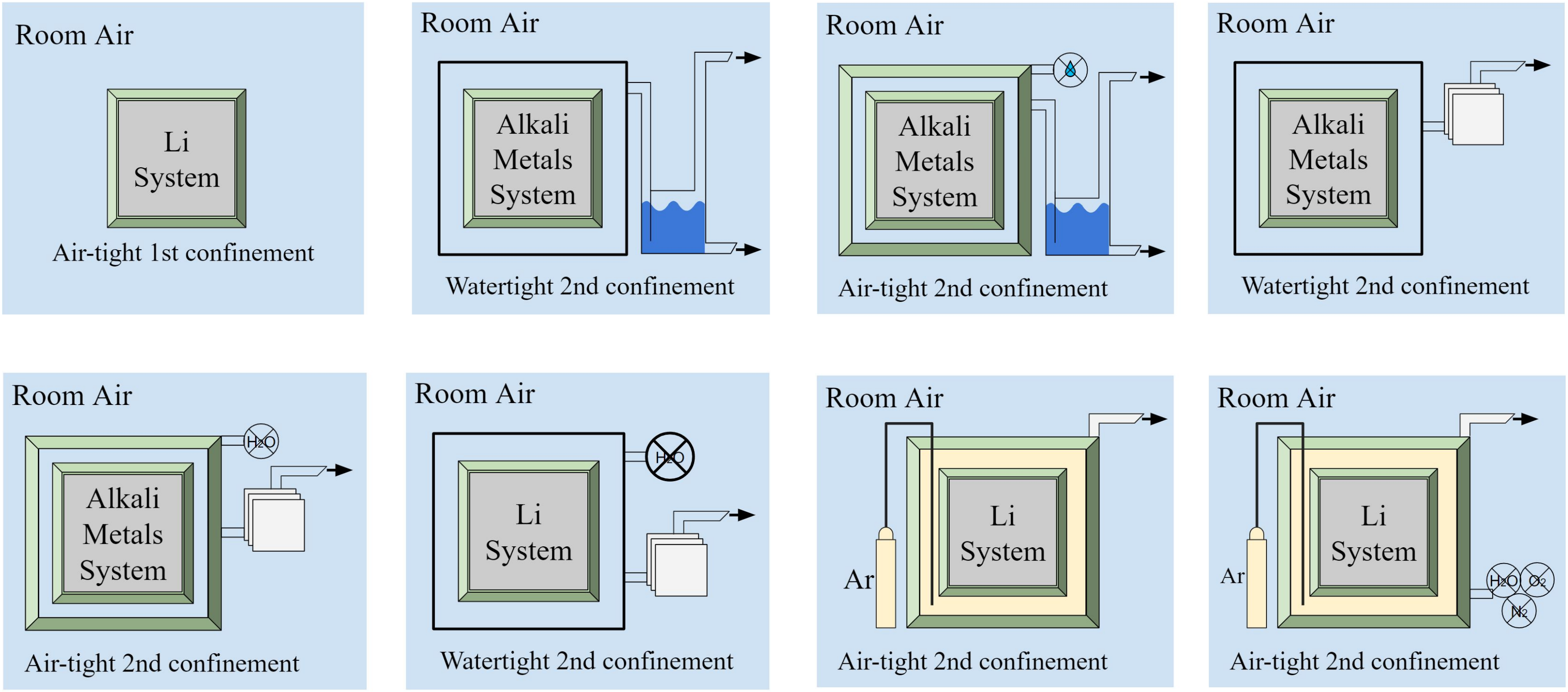


FRIB, Michigan State

What is the optimal secondary enclosure design for LEAP?

yxu@pppl.gov

Design Choices & Comparison



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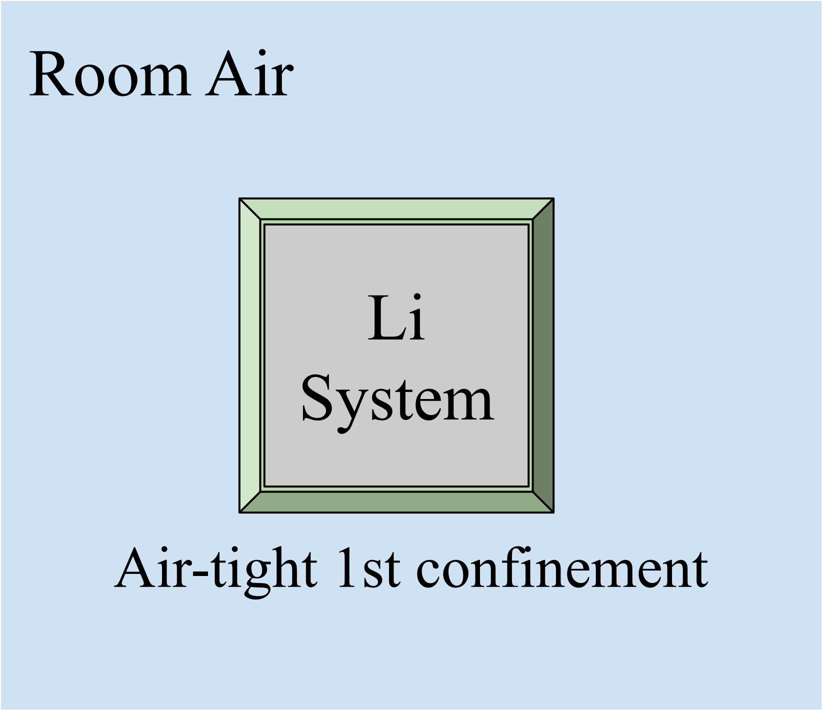
Plasma Control

Case 1: Air-tight 1st confinement



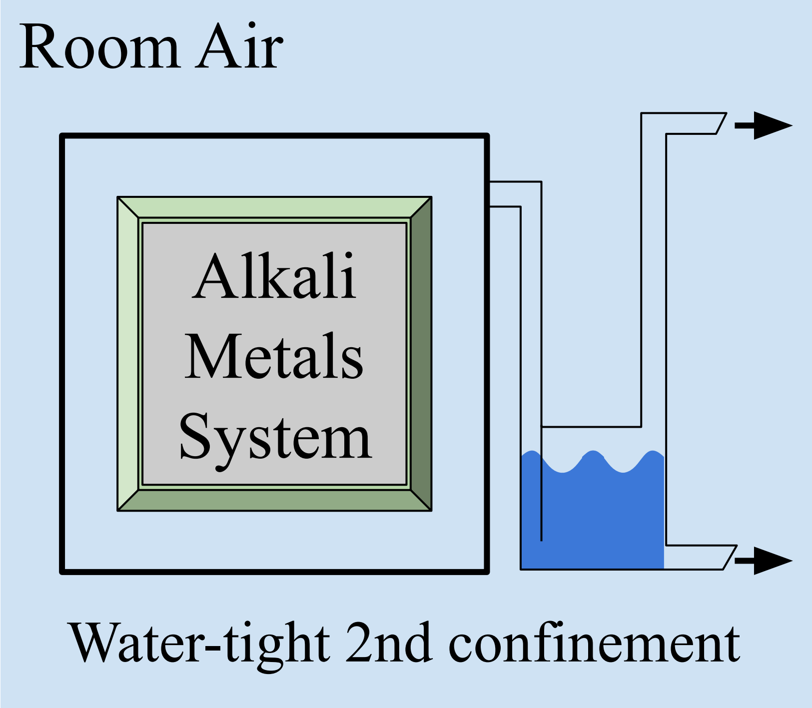
* Numbers are based on qualitative assessment of the hazard (Momo & Yufan)

Full exposure when failure	**Exposure when failure but under control***	**No exposure**
x1	**x0.5**	**x0**

Hazards					
H2 (bulk H2O)	**H2 (moisture)**	**Li Fire (O2)**	**Li Fire (N2)**	**Li Smoke (fire)**	**Asphyxiation**
Severe: 5	**Moderate: 3**	**Moderate: 3**	**Moderate: 3**	**Moderate: 3**	**Low: 2**
2.5	1.5	3	3	3	0

Low facility complexity:
Ventilation & Emergency Exhaust;
H2 Detector

Case 2. ANL Alkali metals facility #1 (wet scrubber)



* Numbers are based on qualitative assessment of the hazard (Momo & Yufan)

Full exposure when failure	Exposure when failure but under control*	No exposure
x1	x0.5	x0

Hazards					
H2 (bulk H2O)	H2 (moisture)	Li Fire (O2)	Li Fire (N2)	Li Smoke (fire)	Asphyxiation
Severe: 5	Moderate: 3	Moderate: 3	Moderate: 3	Moderate: 3	Low: 2
0	1.5	1.5	1.5	1.5	0

High facility complexity:
Ventilation & Emergency Exhaust;
H2 Detector;
Wet scrubber system

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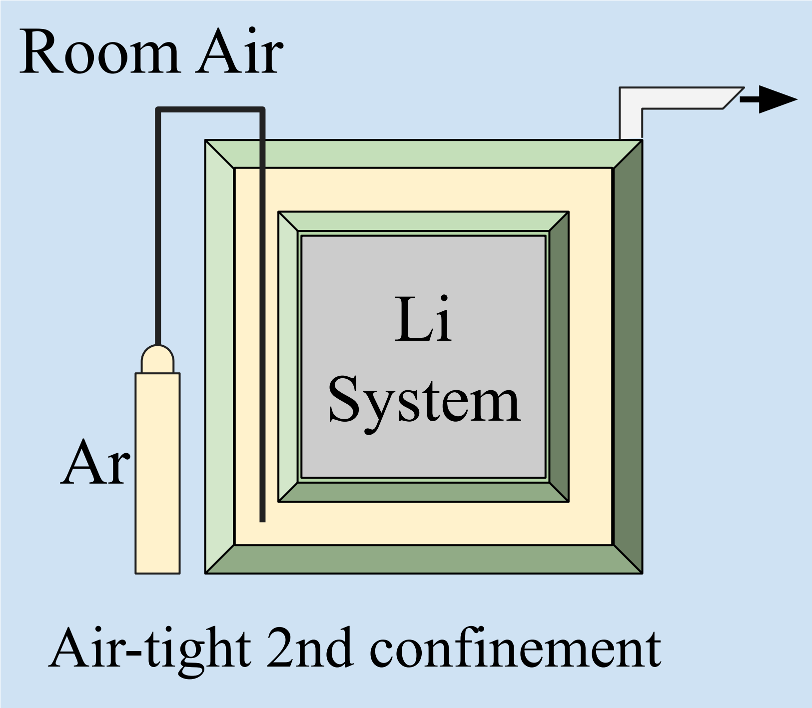
Case 7. FRIB @MSU (air-tight 2nd + Ar-filled)



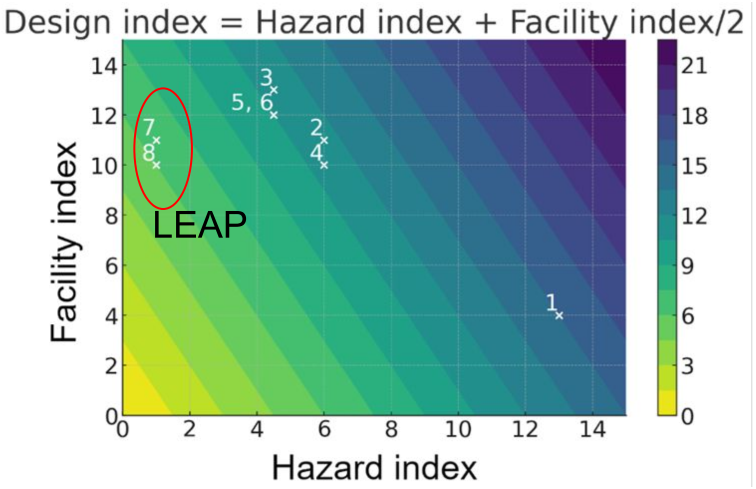
* Numbers are based on qualitative assessment of the hazard (Momo & Yufan)

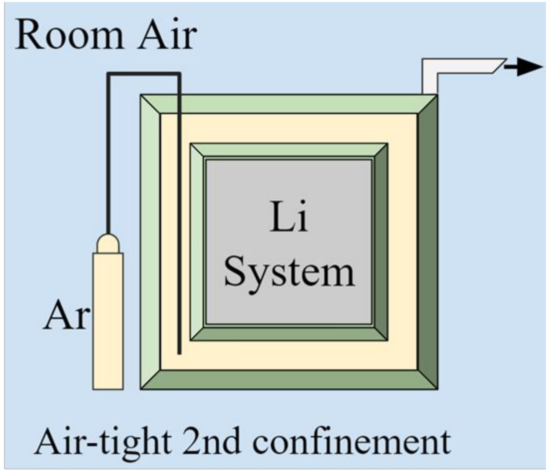
Full exposure when failure	Exposure when failure but under control*	No exposure
x1	x0.5	x0

Hazards					
H2 (bulk H2O)	H2 (moisture)	Li Fire (O2)	Li Fire (N2)	Li Smoke (fire)	Asphyxiation
Severe: 5	Moderate: 3	Moderate: 3	Moderate: 3	Moderate: 3	Low: 2
0	0	0	0	0	1

Low facility complexity:
Ar source;
Airtight 2nd containment;
Ventilation & Emergency Exhaust;

Optimal design for LEAP

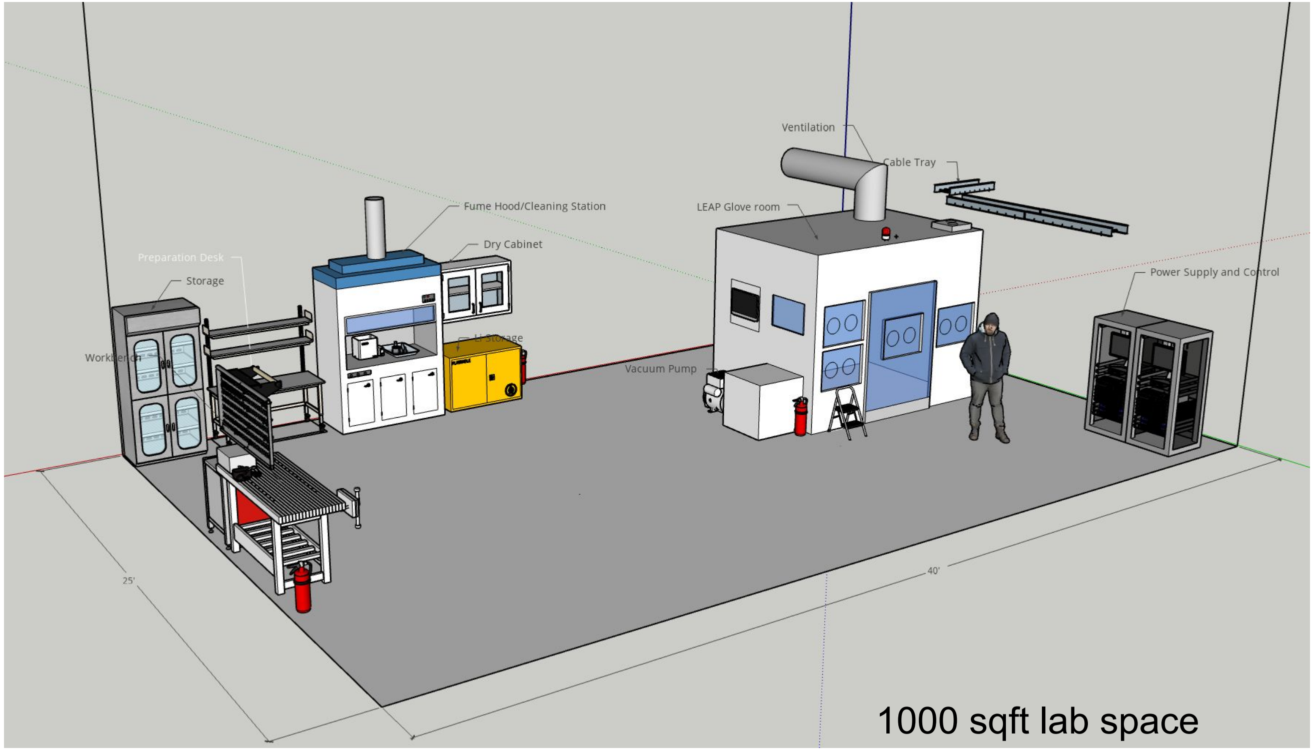




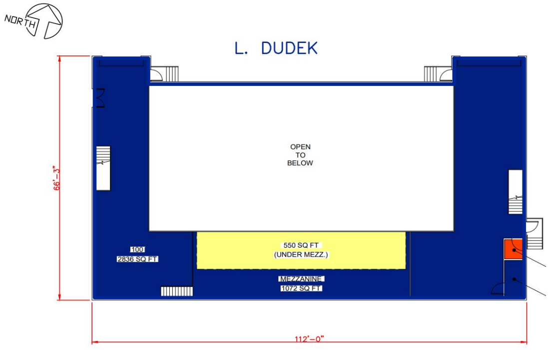
- Optimal design for LEAP at PPPL has been identified:
  Safety working with molten Lithium
  Complexity of facility involved with the design
  Operation and procedure

- Secondary enclosure: Ar-filled, prefab, SS modular glove box, 2m x 3m x 2m

Site & Space



1000 sqft lab space



1st FLOOR

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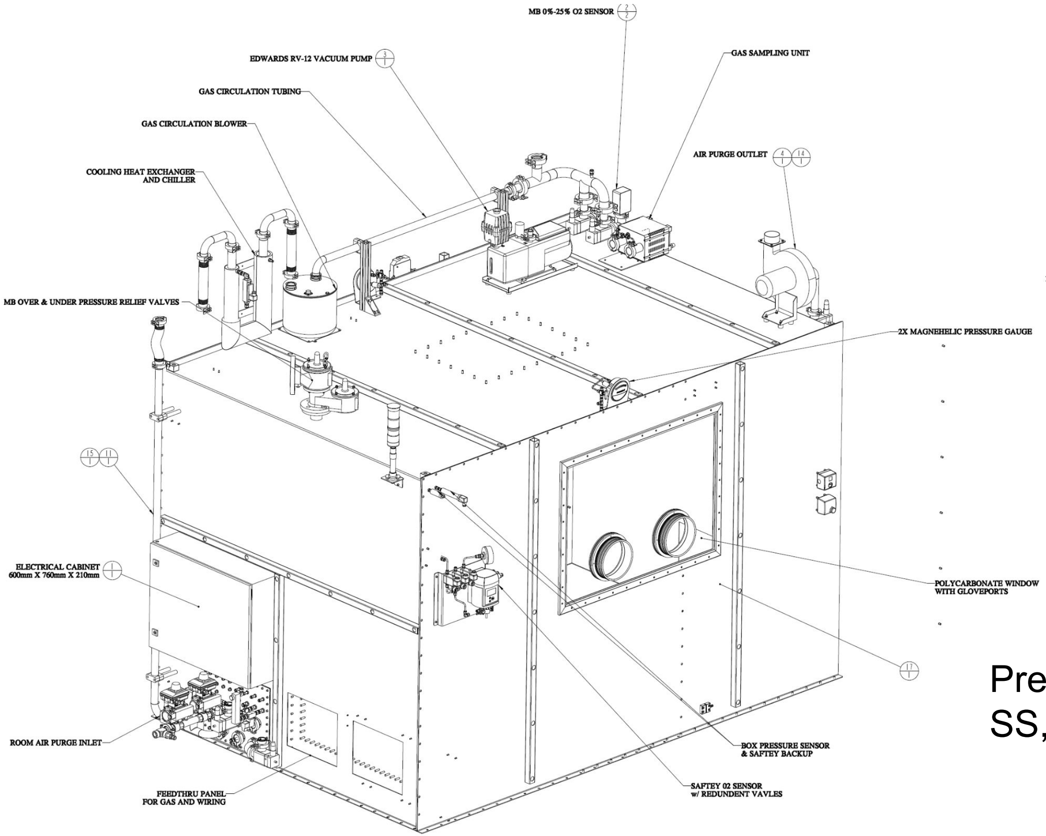
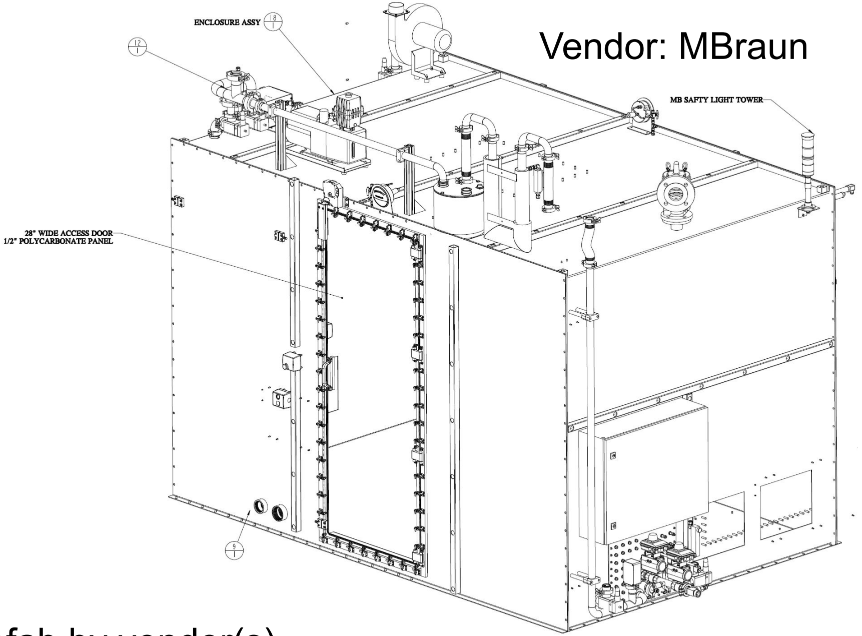
Plasma Control

Gloveroom features





Vendor: MBraun

Prefab by vendor(s)
SS, modularized metal panels

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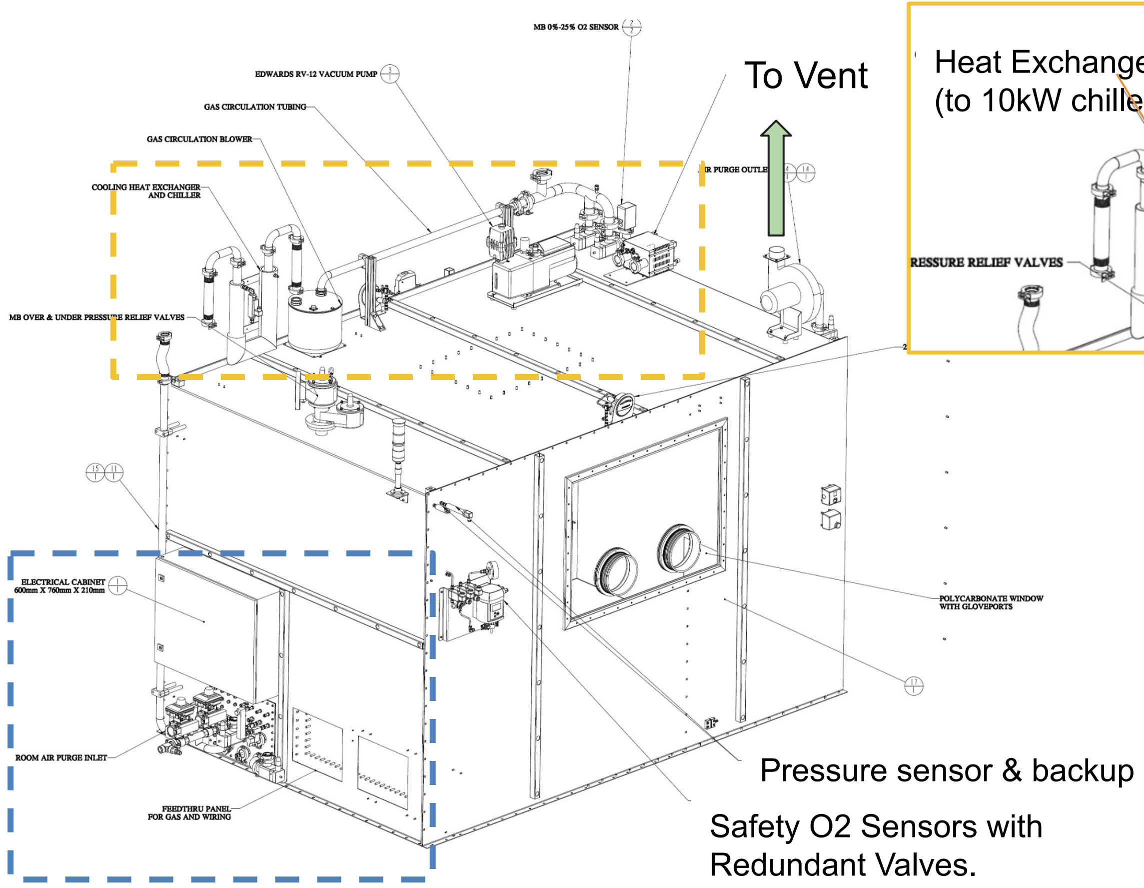
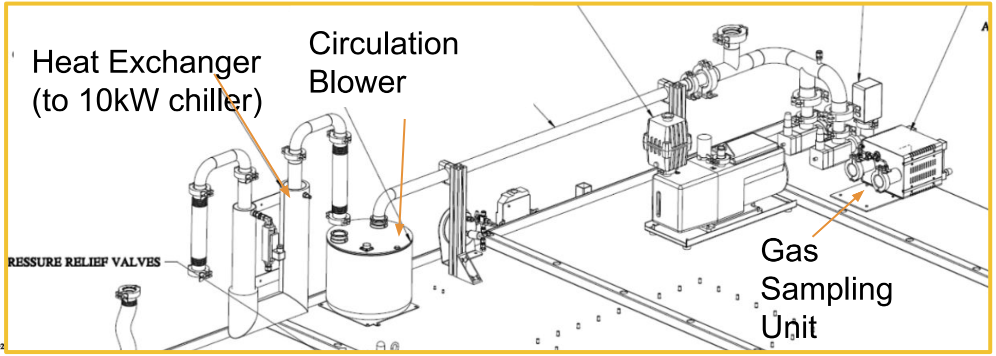
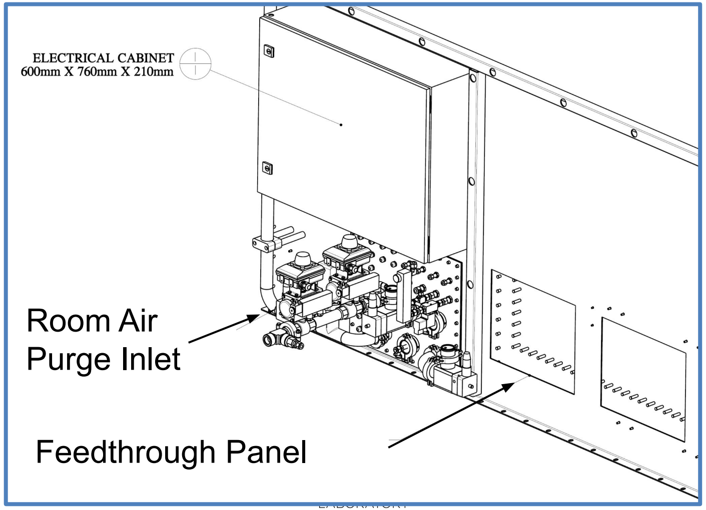
Gloveroom features

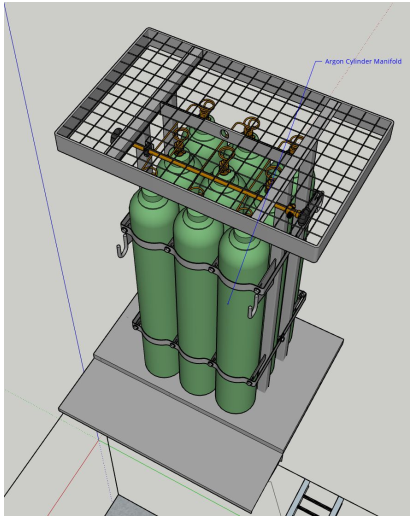






Ar purging

- Purging Ar in the gloveroom can reach lower ppm, but costly.
- If fill the room slowly from the bottom with less mixing → Perfect replacement requires only two 300 ft^3 cylinders.
- Using liquid Ar tanks might be cost-effective for purging event. 200L → 20 cylinders. Outgassing ~ 1% per day
- Our strategy: use an liquid Ar tank during purging event and use a few 300 cu ft cylinders for pressure regulation



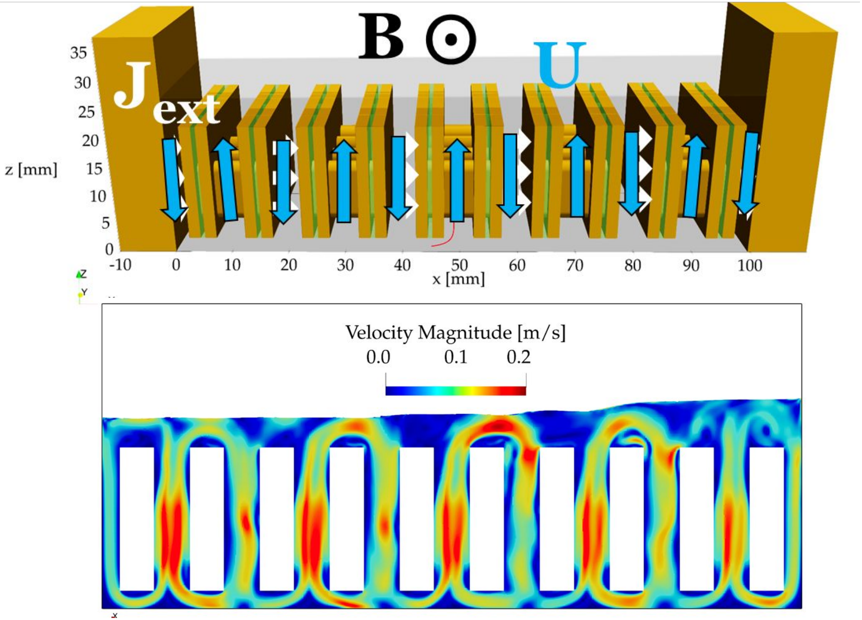
Ar cylinder manifold

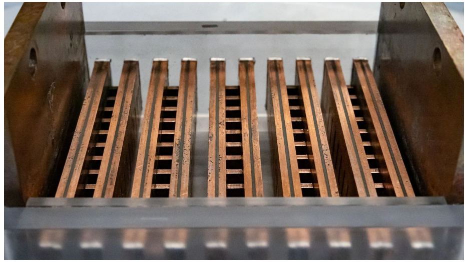
Liquid Ar tanks

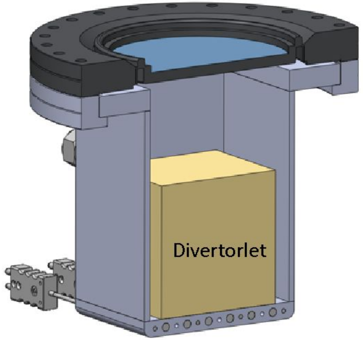
LEAP's scientific missions

Phase I: limited Lithium (~5lb)

Testing liquid lithium divertorlet prototype







Phase II: full inventory (~50lb)
Potential tests:

- Li/LiH plumbing
- Heat and momentum transfer of CPS-lid channel flow
- Gradient B effect on PFC designs
- In-situ material analysis

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Liquid metal governing parameters

LM: Incompressible fluid

Momentum equations:

Re (**Inertia**/viscous),

Ha (**Lorentz**/viscous),

Ra (**Buoyancy**/diffusion),

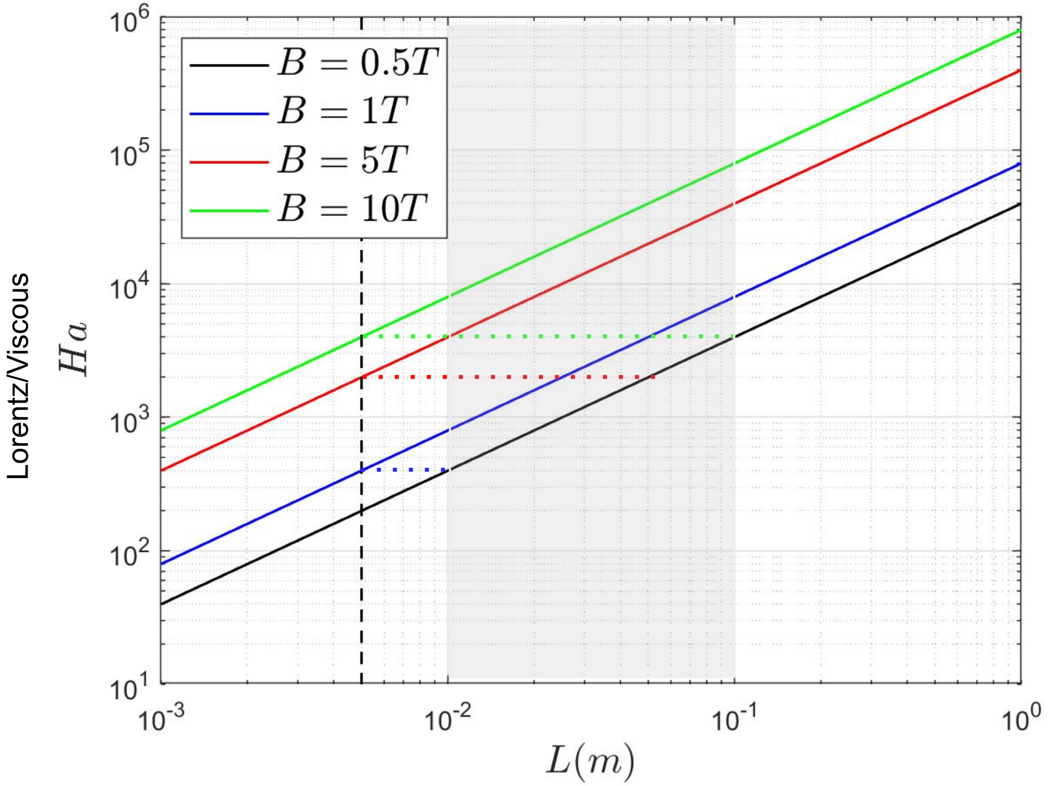
We (Inertia/**surface tension**),

Pr (thermal diffusion/viscous diffusion) – **material properties**. Pr ~ 0.01 in LM

Energy equations: Pe, Nu – **heat transfer efficiency**

Induction equation: Rm (**magnetic induction/magnetic diffusion**), usually Rm<1

Parameter Space



LEAP will be able to simulate small Li flow channels at higher Ha.

For open surface LEAP experiments have a realistic surface tension

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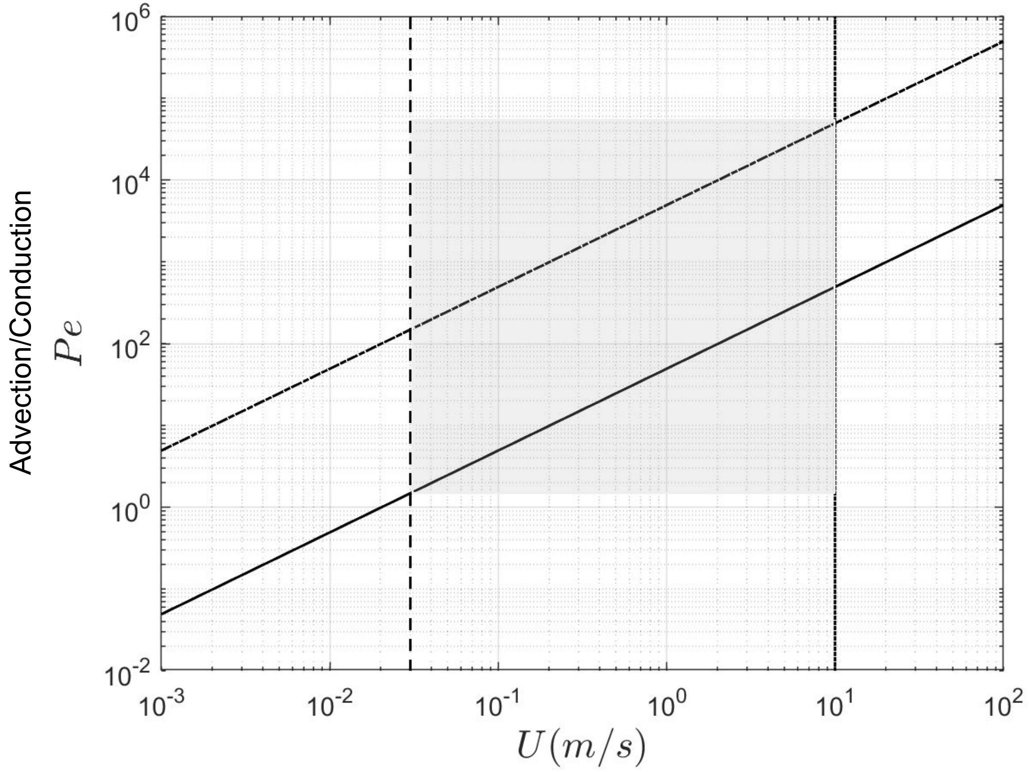
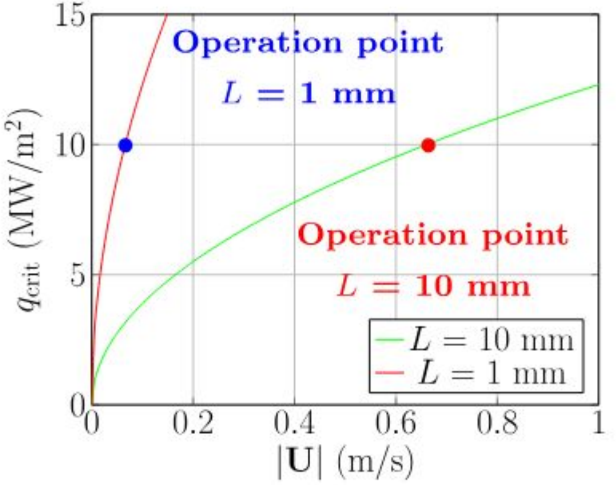
Parameter Space

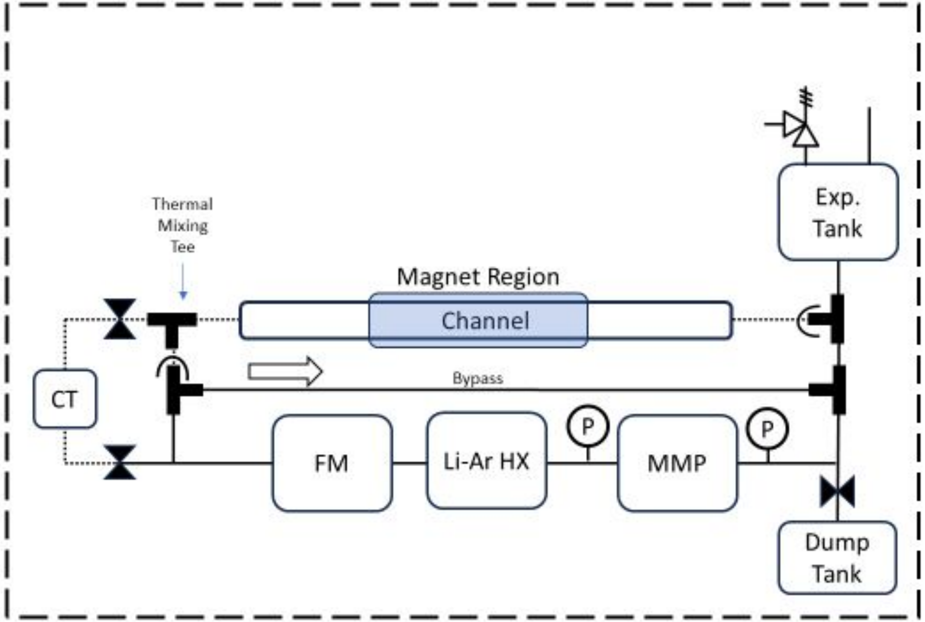




(a) Permissible heat flux for a divertorlets prototype with $L = 10$ mm

Loop design P&ID: Plumbing

Li Plumbing System:

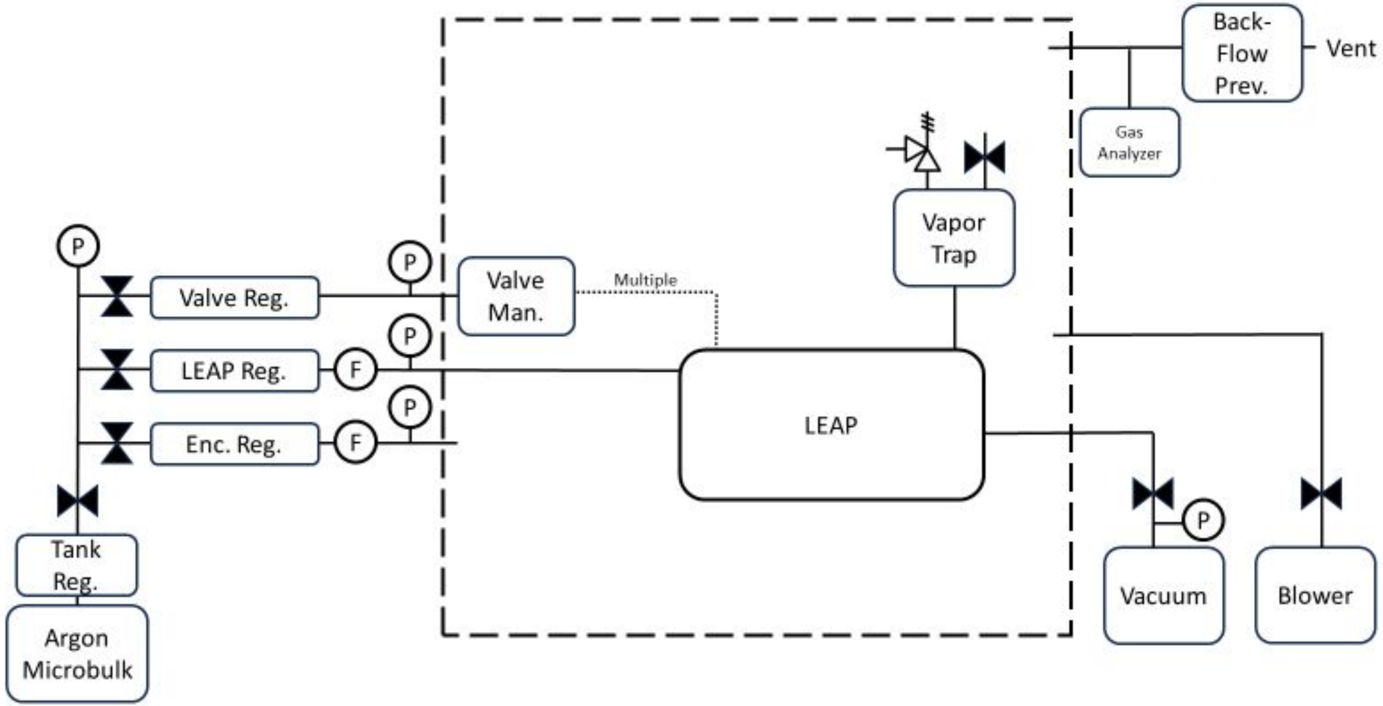


T_Melt < Exp. Tank < 400°C

No valves & limited flow restrictions w/in the main loop.

Loop design P&ID: Gas/Vac/Vent

Gas/Vac/Vent System:



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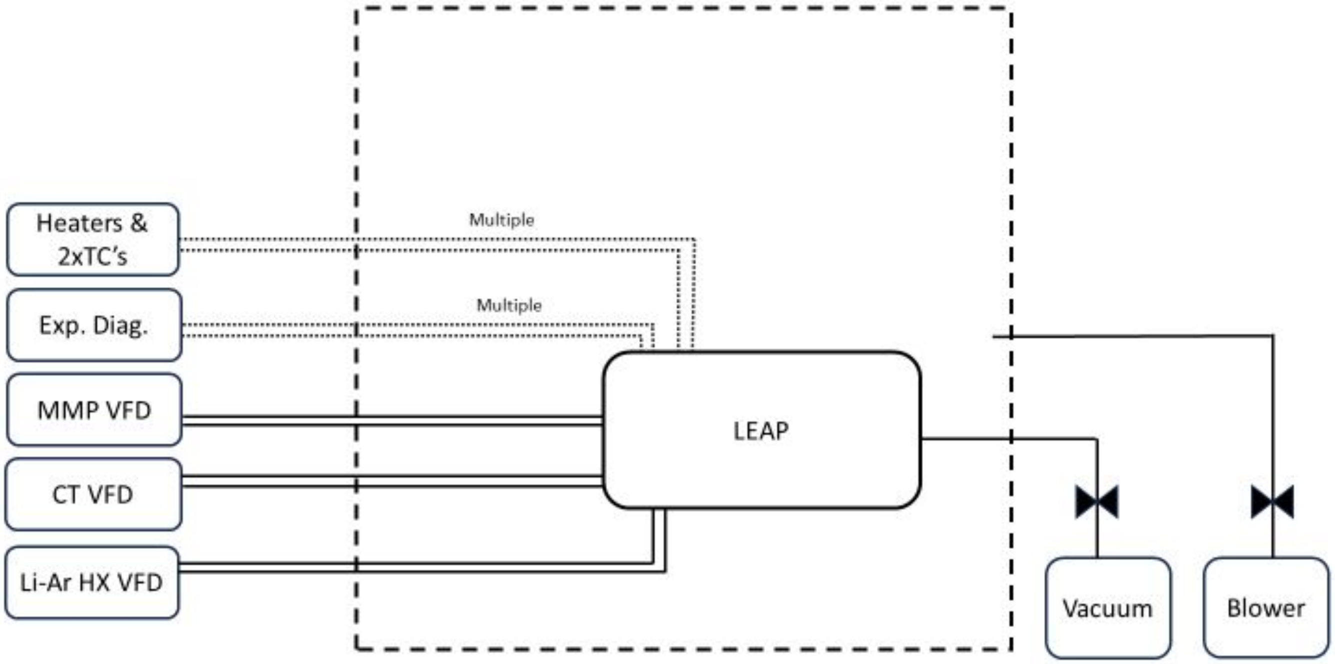
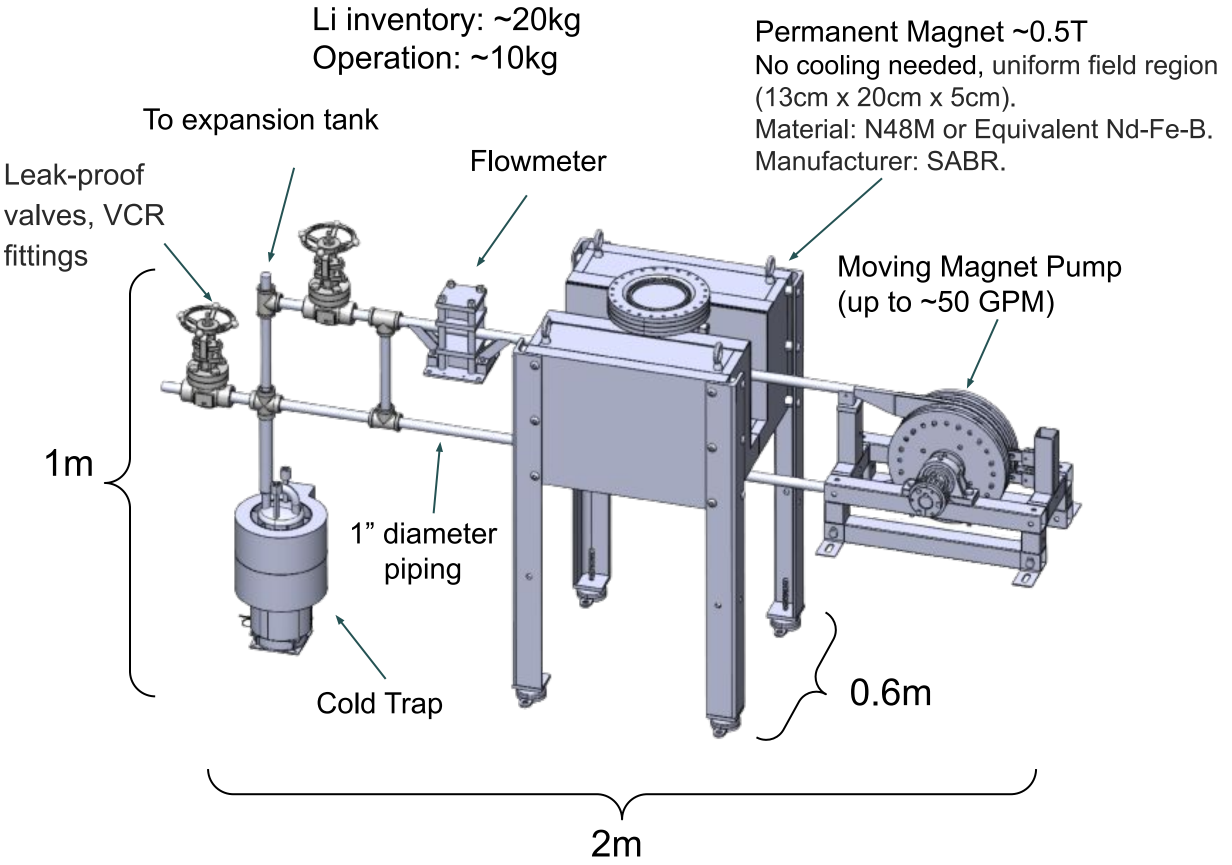
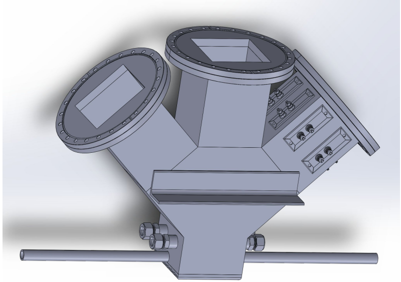
Loop design P&ID: Electrical

Electrical System:

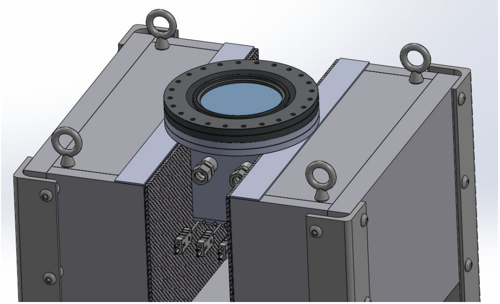


Li Loop Apparatus in LEAP



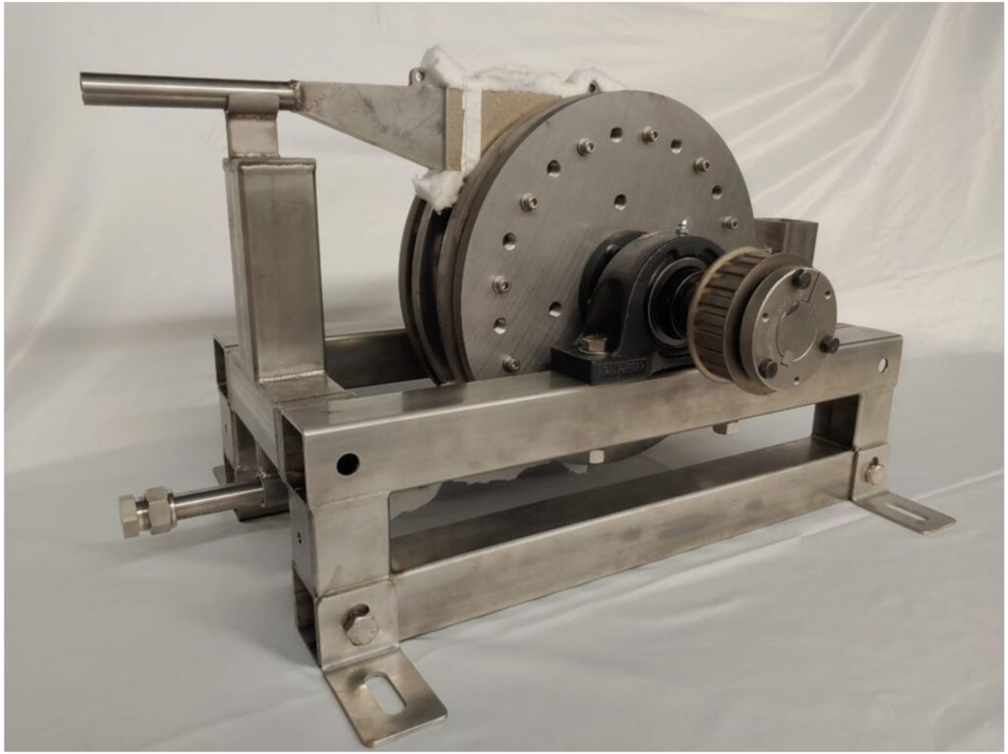


Alternative angled diagnostic flanges

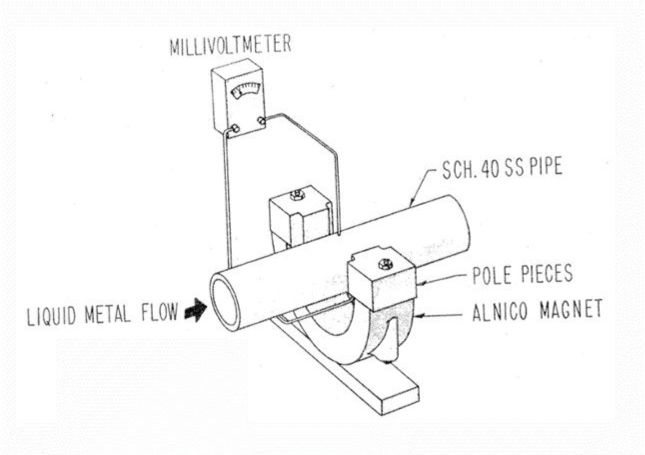


Cartridge heaters & adjustable mounting provisions

Moving Magnet Pump



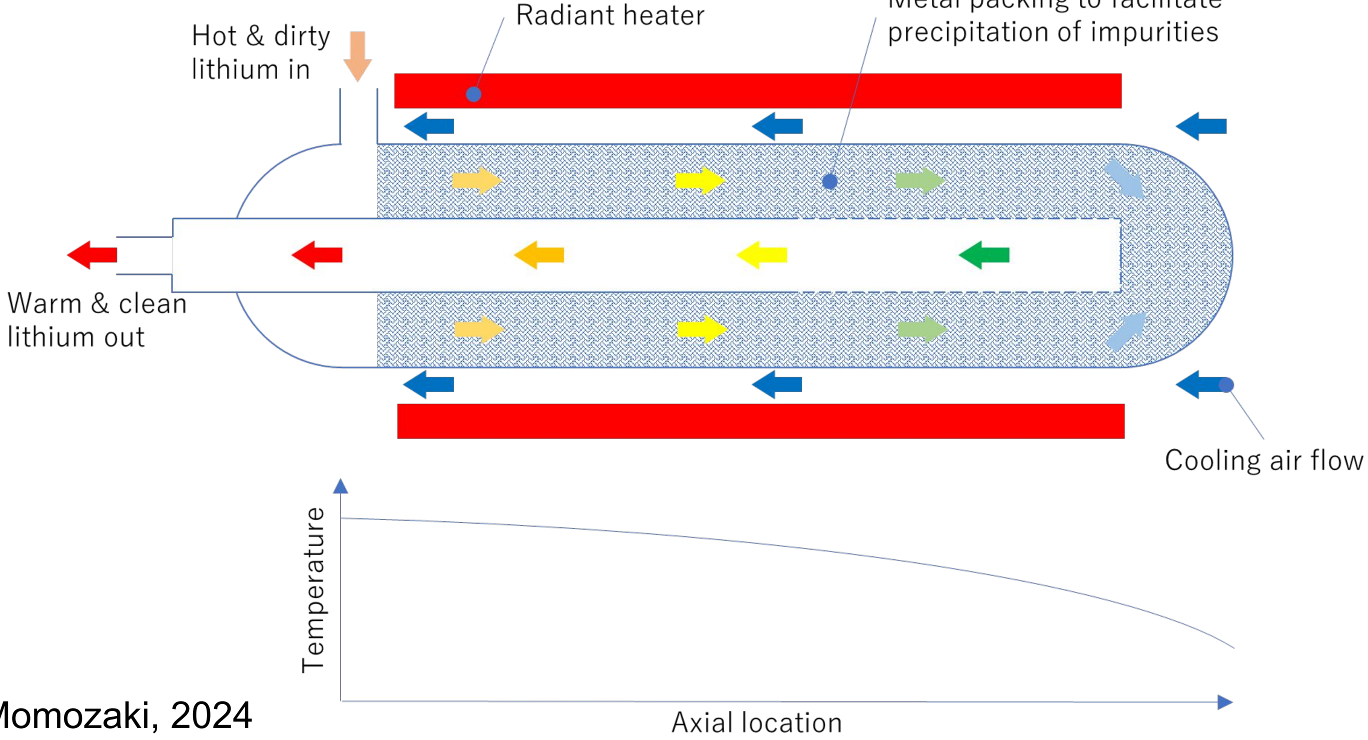
This pump is rated for 550 [°C] and ~ 40 [psid] @ 20 [gpm] w/ Na.



EM Flowmeter

Cold Trap: reduce impurities in Li

Shell & tube style cold trap



Momozaki, 2024

Pipe joint leak detection

Schwartz et al. 2014

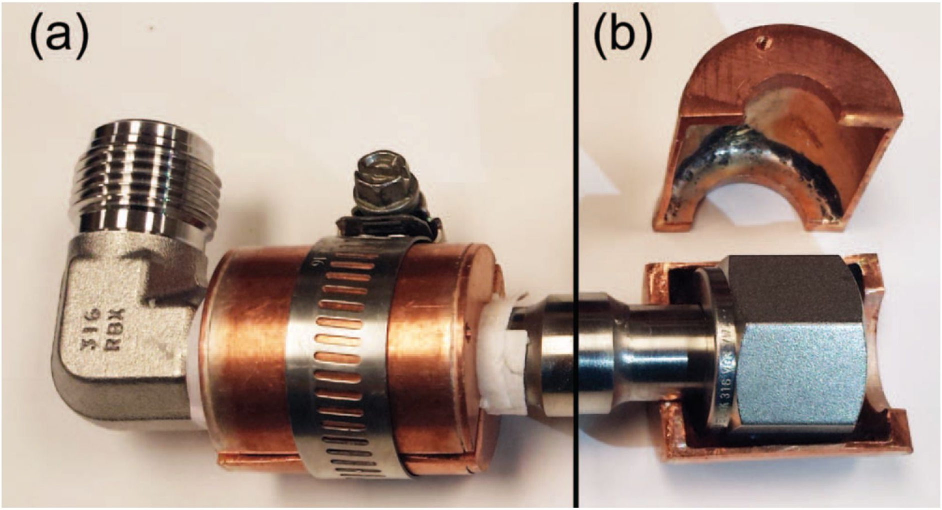


FIG. 1. A mockup of a copper shell surrounding the 5/8 in. VCR joint. In (a), note the white ceramic insulating tape between each end of the shell and the pipe. In (b), note the tapped hole (near top) for connection to a wire lug.

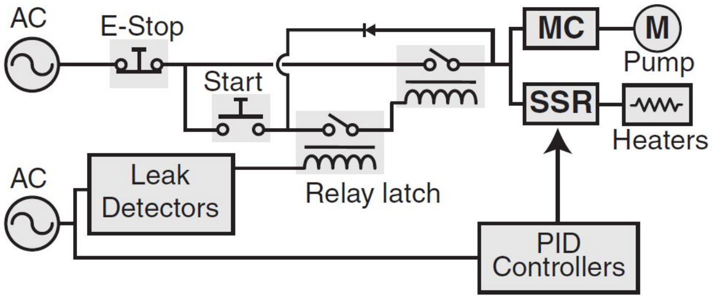
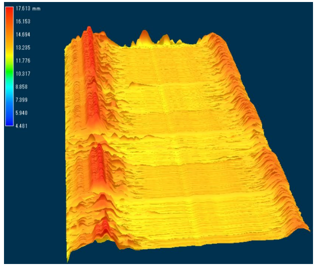


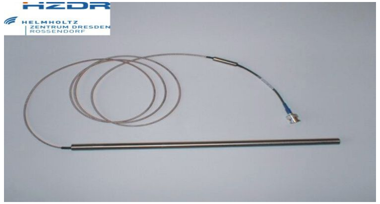
FIG. 3. Block diagram of the interlock system for the heaters and pump motor. If the leak detector circuit detects a fault, or the E-stop button is pushed, power to the pump motor and heaters will be turned off until the leak detectors register no fault on all channels and the start button is pushed. "MC" is the motor controller and "SSR" is the solid state relays.

Available Toolkits

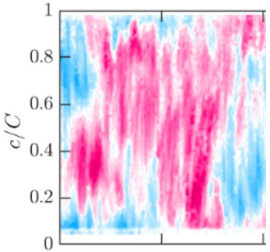
State-of-art LM diagnostics and simulation

Laser profiler
Surface dynamics

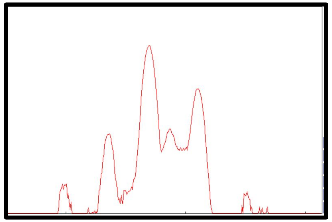




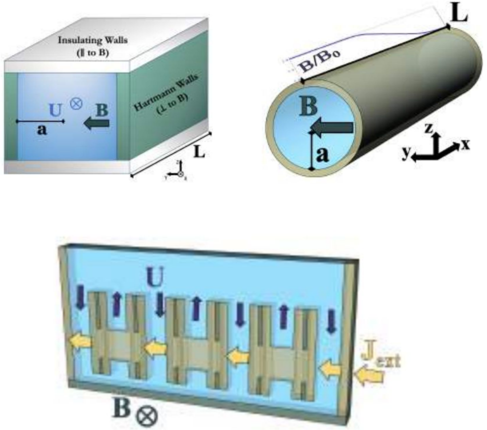
Doppler Probes
Velocity



XRF
High-Z impurity



FreeMHD code



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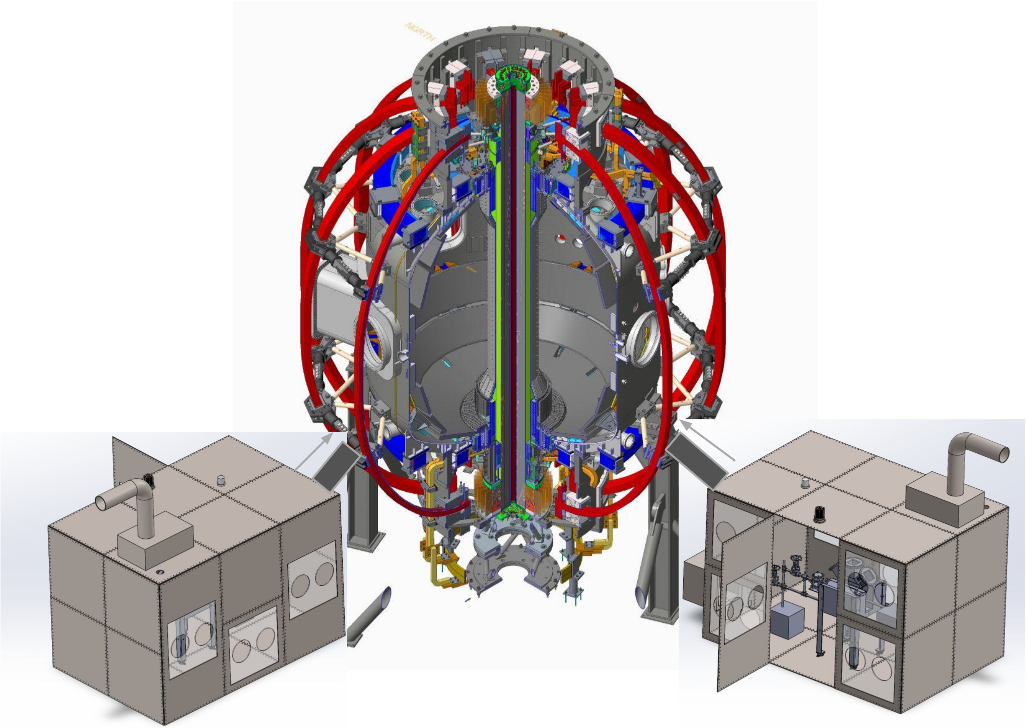
Plasma Control

LEAP as an interface to fusion facilities

- Decentralized lithium distribution system?
- LEAP system can be a real size modularized system for fusion reactors.
- Safe, engineering redundancy.



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Plasma Control

Updates and plans

Design review for the loop design by FY25 Q1

Facility renovation at ESAT

Phase I operation in 2025

Design Committee

R. Majeski	Chairperson, Lithium Expert Committee Chair
R. Ellis	Chief Engineer, TA, Mechanical
D. Cai	Responsible Engineer, Lithium Expert Committee
E. Kolemen	Co-PI, Principle Physicist
Y. Momozaki	Lithium expert, Argonne National Laboratory, External
M. Hvasta	Alkali Metal System Engineer, External
ES&H, ESD*	J. Brockman, J. Fleming, N. Gerrish, J. LaCarrubba, N. Morreale, T. Sandt, M. Swanek, H. Wetzel
F&SS*	K. Jacobs, E. V. Janica, J. Lewis, C. Roames, C. Shaw
Planning*	V. Bommisetty, K. Petura

* Alphabetical order

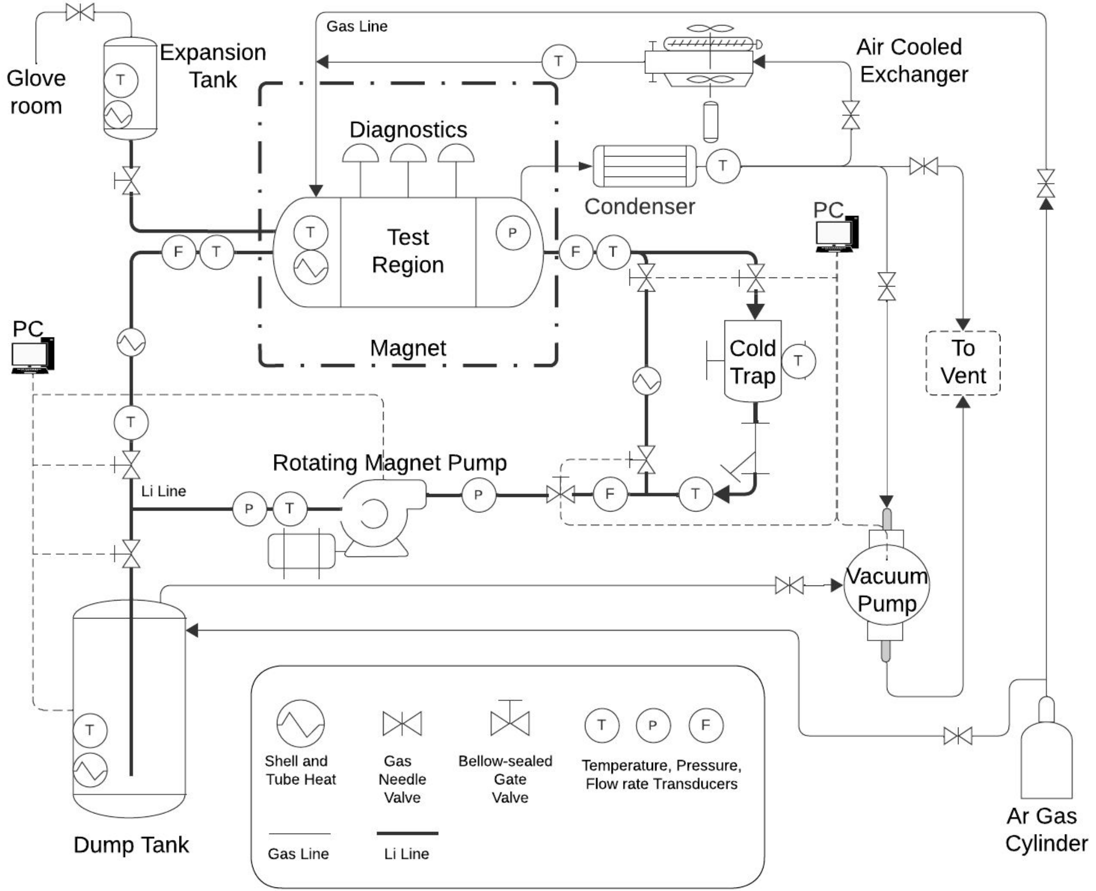
Conclusion

- **LEAP is important for testing full sectors of fast-flowing lithium systems**

- **Lithium Experimental Application Platform (LEAP) design**
  Versatile, reliable, large inventory
  High magnetic field, high heat flux
  LM diagnostics for temperature, velocity, magnetic field, etc.

- **Potential novel integration with fusion reactors.**

Backup slides



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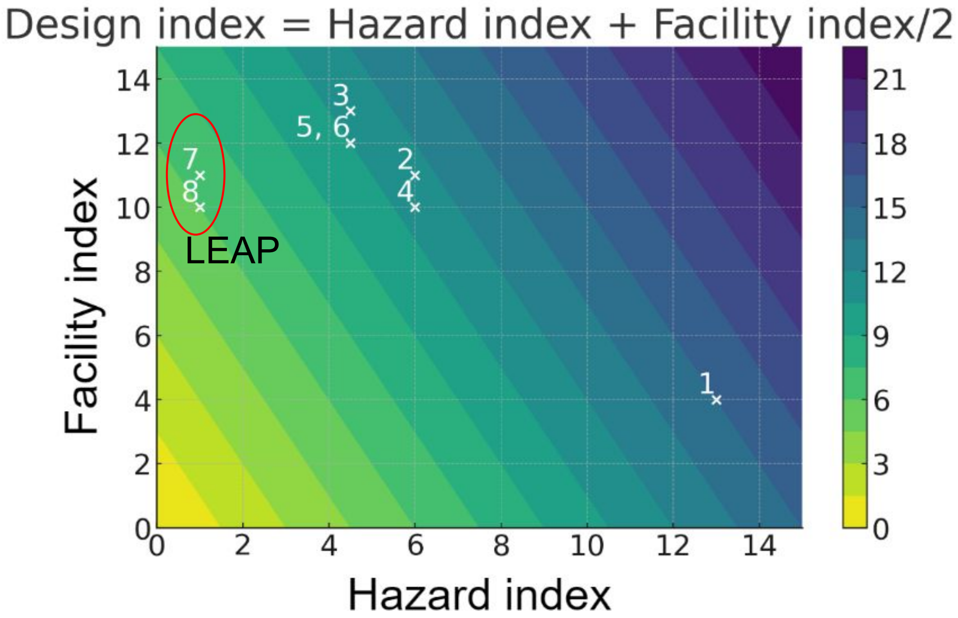
Design Choices & Comparison

- Taking consideration of facility complexity and waste management:
  Watertight 2nd confinement
  Airtight 2nd confinement
  Wet Scrubber (water supply+waste drain)
  Dry Scrubber (waste exhaust)
  Ventilation & Emergency Exhaust
  H2 Detector
  Dehumidifier
  H2O Monitor
  O2/N2 Monitor

- Higher facility index → costly, more infrastructure needs, and often more complicated procedures.

- Normal glovebox is difficult to work with (height ~0.8 [m] & weight limit), unable to modify and expand.



https://docs.google.com/spreadsheets/d/1cdHOzg8biV6Jy7lIJw0-4UiGypue7NUiM4pnxM-yNj8/edit?usp=sharing

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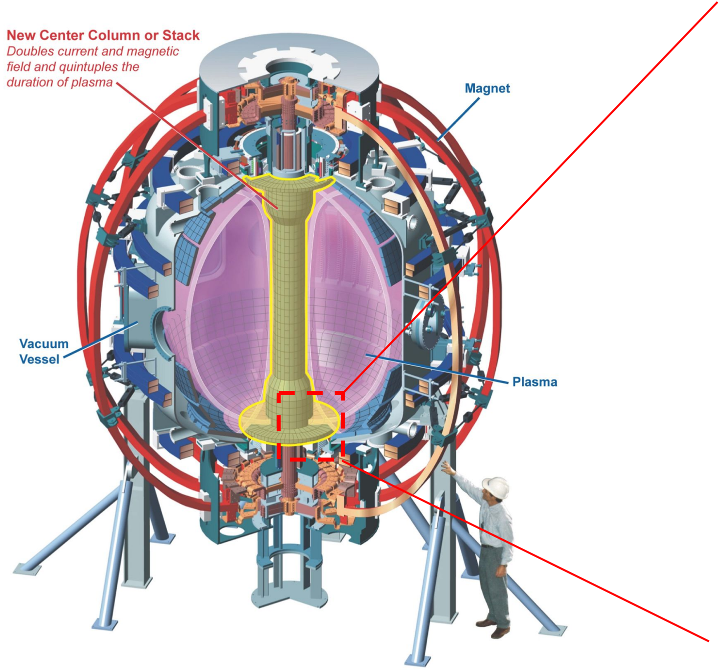
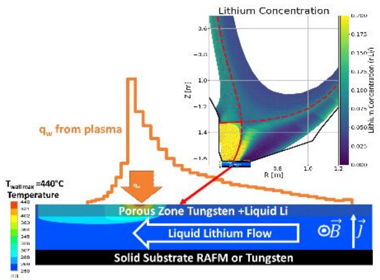
Experimental Platform & LM PFCs

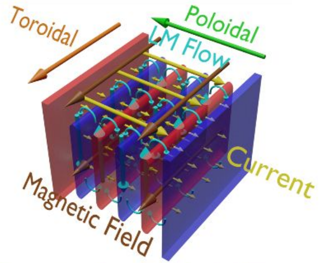
National Spherical Torus Experiment - Upgrade (NSTX-U)



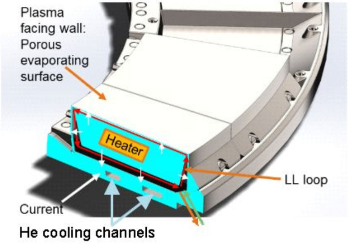
Divertor region: high magnetic field (B_T~1T); high heat flux (~10-100MW/m^2)

Liquid Lithium divertor designs → need subcomponent prototyping

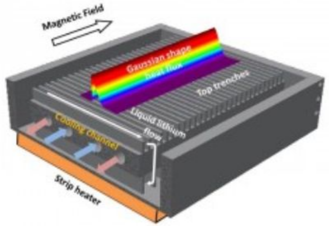




Divertorlets: j×B flows Li in row of vertical cascades



Capillary Porous System with Flow (CPSF)



Li-Metal Infused Trench (LiMIT)
TEMHD drives radial circulating flow

Fast flow designs → high volumetric flow rate
~1 L/s Lithium pumping required for tritium recycling (e.g., Ono et al. 2017).

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#6 Need to show the calculation of how much argon is needed during filling and during operation. And make a decision on the bottle type and size.

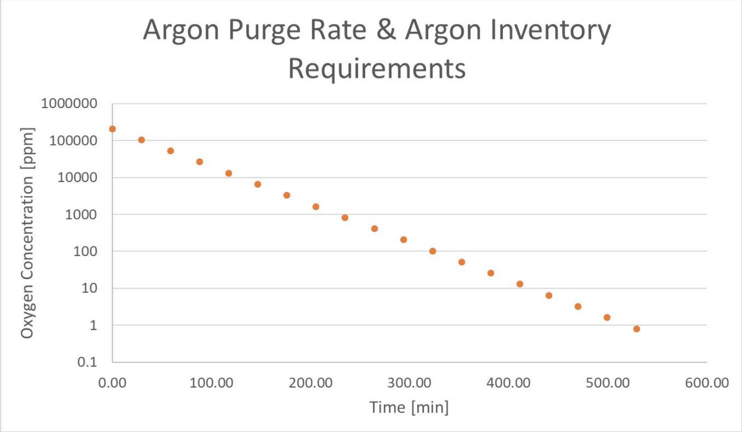
- Sweep-through purging (assumes perfect mixing)

$$Qt = V \ln\left(\frac{C_1}{C_2}\right)$$

- Perfect mixing purging requires seven 300 ft^3 cylinders and three hours to reach 1000 ppm for O2.

- Empirically, vendor recommended using 1 standard bottle of Ar (300 ft^3) to purge a standard 0.82 m^3 glove box with mixing. → ~14 bottles for LEAP.

Variable	Value	Units
Volume, V	12	m^3
Flow Rate, Q	10	ft^3 / min
C1	210000	Initial oxygen concentration [ppm]
C2	1000	Target oxygen concentration [ppm]



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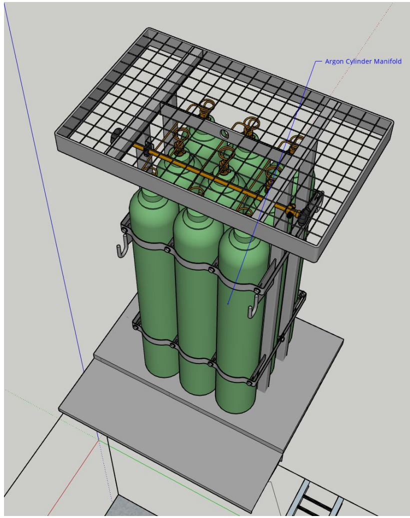
- Purging Ar in the gloveroom can reach lower ppm, but costly.
- If fill the room slowly from the bottom with less mixing → Perfect replacement requires only two 300 ft^3 cylinders.
- Using liquid Ar tanks might be cost-effective for purging event. 200L → 20 cylinders. Outgassing ~ 1% per day
- Our strategy: use an liquid Ar tank during purging event and use a few 300 cu ft cylinders for pressure regulation



Ar cylinder manifold

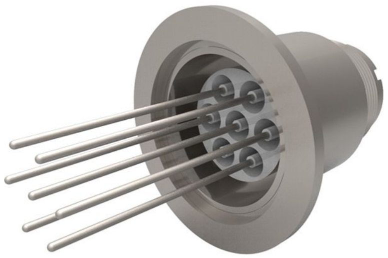
Liquid Ar tanks

#7 Need to resolve issue of water in ESAT. Waterproof design of secondary containment may be sufficient, but the lab would need to change the current requirements for lithium facilities.

Waterline at ESAT has been investigated. No major hazard or concern was raised. Waterproof panels and floor drains could be used to derisk. But the gloveroom is a secondary containment with waterproof walls. The lab might need to change the current requirements for lithium facilities.

#8 There will be many penetration on the glove box for electrical, gas and potential water cooling. For FDR these interfaces need to be shown in detail.

- Interfaces use vacuum-grade KF flanges and hermetic electric feedthroughs for power connection.
- The modularized panel design allows future upgrades and modifications for feedthroughs and connections.



Power Feedthroughs w. KF flange

#9 A fire cabinet is needed to store up to 50 lb of lithium

We agree with the comment that a fire cabinet is needed to initially store up to 50 lb of lithium. After operations, and for the majority of time, lithium will be stored in the dump tank inside the gloveroom.

asecos lithium-ion storage cabinet, 90 Min fire resistant, 6 Shelves, 2 Doors

Item number: M318086W

DENIOS by asecos

- Storage cabinet for undamaged lithium-Ion batteries
- All-round protection: 90 min fire protection from the outside in and inside out
- With tested, liquid-tight spill sump (powder-coated sheet steel). For containment of any leaks from burning or defective batteries
- With permanently self-closing doors and quality oil-damped doors closer. Doors can be locked with a profile cylinder (closing system compatible) and lock indicator (red/green)

Full description >

Vendor visits: Inert & MBraun

On Feb 16, 2024. LEAP team visited Inertcorp, a manufacturer specialized in customized glovebox. Inert is one of the potential vendor for LEAP gloveroom system.

Y. Xu visited MBraun in March 2024.

Laminar Ar filling

Door clamps with O2 lock

Gloves

Feed throughs

Flooring:

Single-piece stainless steel bottom floor

SS fluid dike (no rubber)

Studs and vertical support beams

SAD & Procedure Progress

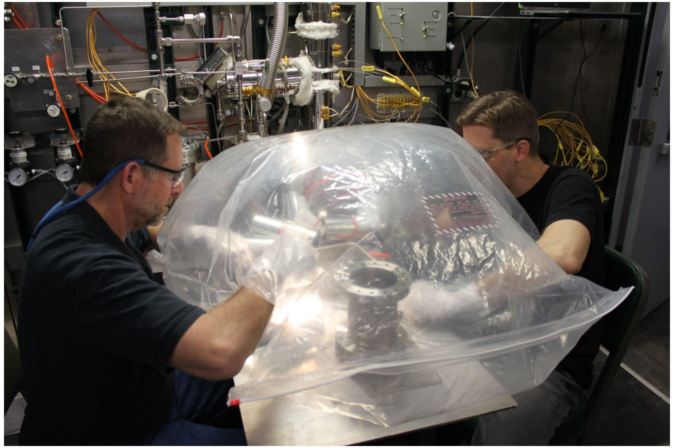
SAD:

A screening for the potential hazards associated with LEAP was performed using a checklist based on SAD for PPPL's LTX and Argonne National Laboratory's "Aware", a work planning and control application, which identifies and analyzes hazards and controls.

Procedure:

In development

Available on LEAP website



Dr. Yoichi Momozaki (Momo)

- Renowned lithium expert at ANL with 20+ year experience
- Designed and operated on liquid lithium facility with hundreds of kg inventory
- Hired part-time for helps on lithium safety and system design on LEAP

Procurement

Inert

Quote: $391,132.36

Timeline: ~20 weeks

Features:

- less expensive
- slower lead time (6 months)
- uncertainty in high-temp

MBraun

Quote: $421,294.00

Timeline: ~16 weeks

Features:

- larger team,
- faster turnover,
- iso9001,
- past collaborations with national lab
- capable of high temperature design
- slightly more expensive

MBRAUN's National lab client list. MBRAUN team members assist in writing the standards for labs and the AGS committee.

- NREL
- Sandia
- Los Alamos
- Lawrence Livermore
- Savannah River
- NETL
- Idaho
- Oak Ridge
- PNNL
- Brookhaven
- Argonne
- AMES
- LBNL

NFPA 484

NFPA 484

Standard for Combustible Metals, Metal Powders, and Metal Dusts

2002 Edition

1.5 Equivalency. Nothing in this standard shall be intended to prevent the use of systems, methods, or devices of equivalent or superior quality, strength, fire resistance, effectiveness, durability, and safety over those prescribed by this standard, provided technical documentation is made available to the authority having jurisdiction to demonstrate equivalency, and the system, method, or device is approved for the intended purpose.

5.4.2 Solid Lithium Storage.

5.4.2.1 Solid lithium shall be stored only on the ground floor.

5.4.2.2 There shall be no basement or depression below the lithium storage area into which water or molten metal shall be allowed to flow or fall during a fire.

5.4.2.3 The solid lithium storage area shall be isolated from other areas so that water cannot enter by spray or drainage from automatic sprinkler systems or any other water source.

Lithium Vapor Pressure

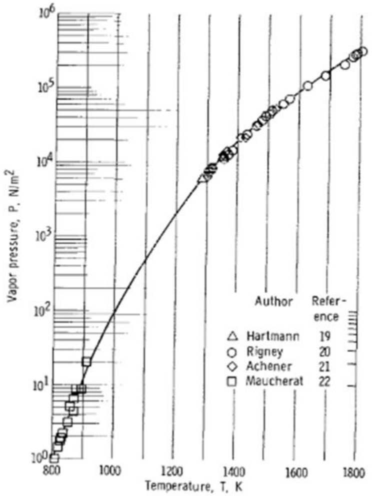


Figure 8. - Lithium vapor pressure (log P = 10. 015 - 8064. 5/T).

$$\rho = 562 - 0.100\ T$$

$$\log P = 10.015 - \frac{8064.5}{T}$$

COMPILATION OF THERMOPHYSICAL PROPERTIES OF LIQUID LITHIUM, NASA TN D-4650
(https://ntrs.nasa.gov/api/citations/19680018893/downloads/19680018893.pdf)

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Cavitation # (Ca), Ca >> 1 = No Cavitation

Cavitation Number

The **Cavitation Number (Ca)** or **Cavitation Parameter** is a dimensionless number used in flow calculations. It is conventional to characterize how close the pressure in the liquid flow is to the vapor pressure (and therefore the potential for cavitation) by means of the cavitation number.

The Cavitation Number can be expressed as:

$$\mathrm{Ca} = \frac{p - p_v}{\frac{1}{2}\rho v^2}$$

where

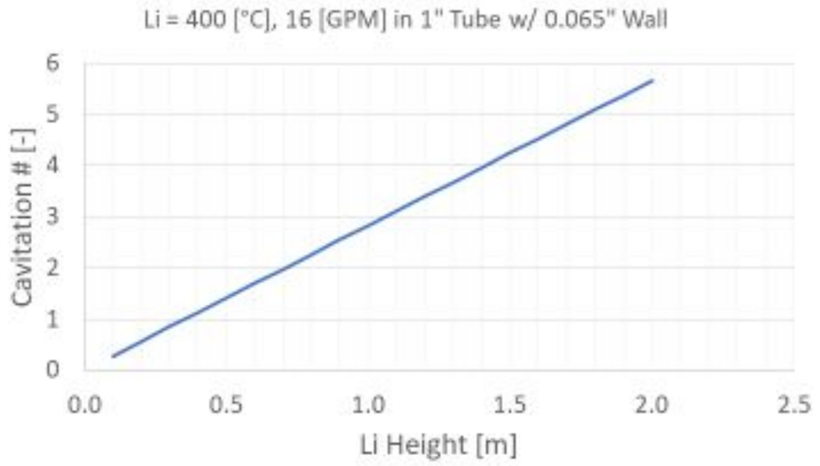
CA = *Cavitation Number*

p = *local pressure (Pa)*

p_v = *vapor pressure of the fluid (Pa)*

ρ = *density of the fluid (kg/m³)*

v = *velocity of fluid (m/s)*



Cavitation # Operating Space

Green > 1, Red < 1

			Velocity [m/s]												
Pressure [PSI]	Pressure [Pa]	Height [m] (ΔP = ρ*g*h)	0.001	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3
0.001	6.89476	0.001421307	2.78E+04	4.45E-01	1.11E-01	4.95E-02	2.78E-02	1.78E-02	1.24E-02	9.09E-03	6.96E-03	5.50E-03	4.45E-03	3.68E-03	3.09E-03
0.1	689.476	0.142130695	2.79E+06	4.46E+01	1.11E+01	4.96E+00	2.79E+00	1.78E+00	1.24E+00	9.10E-01	6.97E-01	5.51E-01	4.46E-01	3.69E-01	3.10E-01
0.2	1378.952	0.284261389	5.58E+06	8.92E+01	2.23E+01	9.91E+00	5.58E+00	3.57E+00	2.48E+00	1.82E+00	1.39E+00	1.10E+00	8.92E-01	7.37E-01	6.19E-01
0.3	2068.428	0.426392084	8.36E+06	1.34E+02	3.35E+01	1.49E+01	8.36E+00	5.35E+00	3.72E+00	2.73E+00	2.09E+00	1.65E+00	1.34E+00	1.11E+00	9.29E-01
0.4	2757.904	0.568522779	1.12E+07	1.78E+02	4.46E+01	1.98E+01	1.12E+01	7.14E+00	4.96E+00	3.64E+00	2.79E+00	2.20E+00	1.78E+00	1.47E+00	1.24E+00
0.5	3447.38	0.710653474	1.39E+07	2.23E+02	5.58E+01	2.48E+01	1.39E+01	8.92E+00	6.19E+00	4.55E+00	3.48E+00	2.75E+00	2.23E+00	1.84E+00	1.55E+00
0.6	4136.856	0.852784168	1.67E+07	2.68E+02	6.69E+01	2.97E+01	1.67E+01	1.07E+01	7.43E+00	5.46E+00	4.18E+00	3.30E+00	2.68E+00	2.21E+00	1.86E+00
0.7	4826.332	0.994914863	1.95E+07	3.12E+02	7.81E+01	3.47E+01	1.95E+01	1.25E+01	8.67E+00	6.37E+00	4.88E+00	3.85E+00	3.12E+00	2.58E+00	2.17E+00
0.8	5515.808	1.137045558	2.23E+07	3.57E+02	8.92E+01	3.96E+01	2.23E+01	1.43E+01	9.91E+00	7.28E+00	5.58E+00	4.40E+00	3.57E+00	2.95E+00	2.48E+00
0.9	6205.284	1.279176252	2.51E+07	4.01E+02	1.00E+02	4.46E+01	2.51E+01	1.61E+01	1.12E+01	8.19E+00	6.27E+00	4.96E+00	4.01E+00	3.32E+00	2.79E+00
1	6894.76	1.421306947	2.79E+07	4.46E+02	1.12E+02	4.96E+01	2.79E+01	1.78E+01	1.24E+01	9.10E+00	6.97E+00	5.51E+00	4.46E+00	3.69E+00	3.10E+00
			Cavitation # [-]												

ma
:rol

Predicting Cavitation

Sigma is defined below:

$$\sigma = \frac{(P1\text{-}PV)}{(P1\text{-}P2)}$$

Where:

P1 = Upstream pressure (psia)

P2 = Downstream pressure (psia)

PV = Vapor pressure of the liquid at flowing temperature

σ ≥ 2.0	No cavitation
1.7 < σ < 2.0	Hardened trim provides sufficient protection
1.5 < σ < 1.7	Some cavitation, single-stage trim may work
1.0 < σ < 1.5	Potential for severe cavitation, multi-stage pressure drop trim required
σ < 1.0	Flashing

Embedded in Trimteck's AccuValve Sizing & Specification Software is the Sigma Cavitation Index for **predicting the potential for cavitation** given a set of valve process parameters. Sigma is the most widely-accepted and precise cavitation index used to quantify and predict cavitation in control valves. Simply put, Sigma is the ratio of the potential for resisting formation of vapor bubbles to the potential for causing formation of vapor bubbles.

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Rhoads, 2013

Parameter	Definition	Value	Ratio of ...
Reynolds number	$\mathrm{Re} = \dfrac{\mathrm{v}_0 L}{\nu}$	$5000 \lesssim \mathrm{Re} \lesssim 10^4$	Inertial to viscous forces
Magnetic Reynolds number	$\mathrm{R_m} = \mu\sigma L \mathrm{v}_0$	$10^{-3} \lesssim \mathrm{R_m} \lesssim 10^{-2}$	Magnetic advection to magnetic diffusion
Interaction parameter	$N = \dfrac{\sigma L B_0^2}{\rho \mathrm{v}_0}$	$0 \lesssim N \lesssim 20$	Electromagnetic to inertial forces
Hartmann number	$\mathrm{Ha} = L B_0 \sqrt{\dfrac{\sigma}{\rho\nu}}$	$0 \lesssim \mathrm{Ha} \lesssim 100$	Electromagnetic to viscous forces
Péclet number	$\mathrm{Pe} = \dfrac{\rho c_p \mathrm{v}_0 L}{\lambda}$	$100 \lesssim \mathrm{Pe} \lesssim 300$	Advection to diffusion
Prandtl number	$\mathrm{Pr} = \dfrac{\nu}{\kappa}$	$\mathrm{Pr} = 0.048$	Viscous to thermal diffusion rates
Magnetic Prandtl number	$\mathrm{Pr_m} = \dfrac{\nu}{\lambda}$	$\mathrm{Pr_m} = 1.62 \times 10^{-6}$	Viscous to magnetic diffusion rates
Nusselt number	$\mathrm{Nu} = \dfrac{hL}{k}$	$10 \lesssim \mathrm{Nu} \lesssim 40$	Convective to conductive heat transfer
Froude number	$\mathrm{Fr} = \dfrac{\mathrm{v}_0}{\sqrt{gd}}$	$0.1 \lesssim \mathrm{Fr} \lesssim 0.7$	Inertial to gravity forces
Capillary number	$\mathrm{Ca} = \dfrac{\rho\nu \mathrm{v}_0}{\gamma}$	$10^{-4} \lesssim \mathrm{Ca} \lesssim 10^{-3}$	Viscous forces to surface tension
Weber number	$\mathrm{We} = \dfrac{\rho \mathrm{v}_0^2 d}{\gamma}$	$0.5 \lesssim \mathrm{We} \lesssim 5$	Inertial forces to surface tension
Bond number	$\mathrm{Bo} = \dfrac{\rho g d^2}{\gamma}$	$10 \lesssim \mathrm{Bo} \lesssim 75$	Gravitational force to surface tension

Table D.1: Dimensionless parameters and values for the Liquid Metal Experiment.

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Table 2.1: Various properties of liquid galinstan and lithium at working/operating conditions.

Liquid / Property	Galinstan [69, 27]	Lithium [20, 45]	Tin [78, 6, 35, 52]
Chemical make-up	67%Ga 20.5%In 12.5%Sn	100% Li	100% Sn
Reference temp.	$300[K]$	$600[K]$	$900[K]$
Density	$6.4 \times 10^3 [kg/m^3]$	$5.02 \times 10^2 [kg/m^3]$	$6.72 \times 10^3 [kg/m^3]$
Dynamic Viscosity	$2.4 \times 10^{-3} [Pa \cdot s]$	$4 \times 10^{-4} [Pa \cdot s]$	$8.62 \times 10^{-4} [Pa \cdot s]$
Electrical conductivity	$3.1 \times 10^6 [S/m]$	$3.34 \times 10^6 [S/m]$	$1.74 \times 10^6 [S/m]$
Thermal conductivity	$1.65 \times 10^1 [W/m \cdot K]$	$4.6 \times 10^1 [W/m \cdot K]$	$3.97 \times 10^1 [W/m \cdot K]$
Specific heat	$3.65 \times 10^2 [J/kg \cdot K]$	$4.169 \times 10^3 [J/kg \cdot K]$	$2.43 \times 10^2 [J/kg \cdot K]$
Surface Tension	$5.33 - 6.2 \times 10^{-1} [N/m]$	$3.83 \times 10^{-1} [N/m]$	$5.39 \times 10^{-1} [N/m]$