MPEX Users Research Forum (MURF) 2021:

Needs for flowing liquid lithium and metal systems for MPEX

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Outline

- Background
  - Why interest in liquid lithium/metal research
  - Why MPEX?
- Questions that need to be asked/answered
  - Recycling
  - Pumping and Recovery of H/D (T surrogate)
  - Helium Pumping, can it be done?
  - Heat flux handling
- Flowing LM Concepts
  - LiMIT
  - FLiLi
  - Flowing Porous System
  - Divertolets
  - LiH Separation – Magnetic Centrifuge
  - Distillation Column
- What would be needed for MPEX
  - Lithium handling and flow systems
    - Glove Box (stationary and mobile)
    - Lithium Loop
    - Li Injection system?
    - Lithium inventory
  - Plasma Diagnostics
- Conclusion

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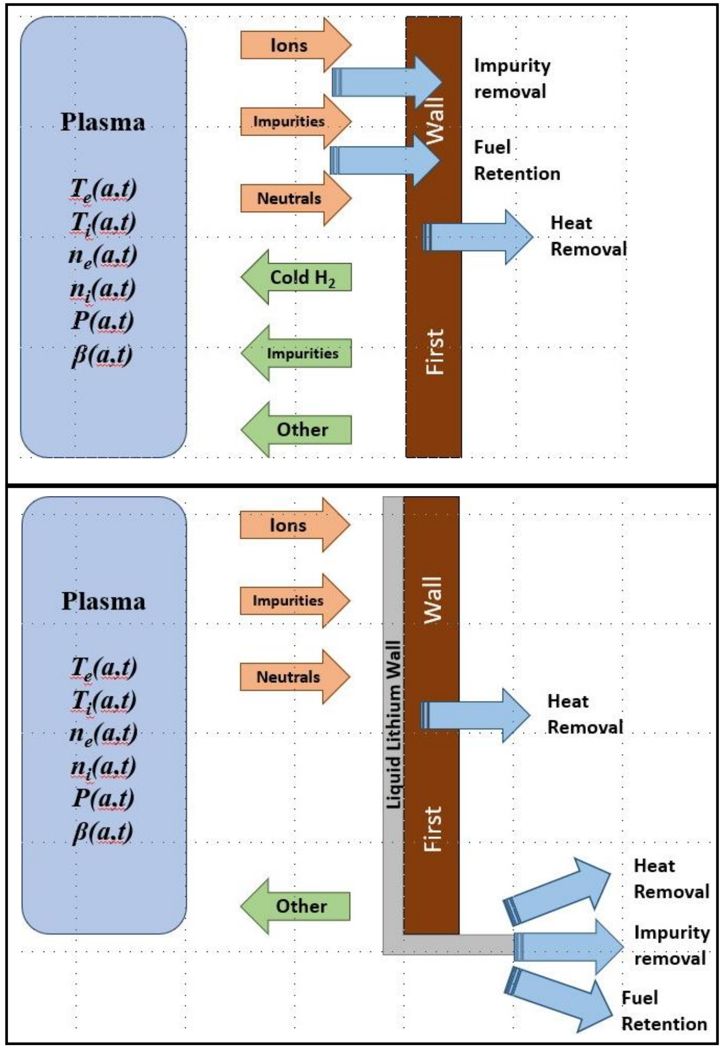
Why liquid metal research?

Complex behavior of materials and plasma - solids

- Incident high energy ions and neutrals will have a significant impact on reactor surfaces
- Damage
    - Displacement of atoms within the lattice structure of the materials
    - Leads to embrittlement
- Surface structure formation
    - Fuzz
    - Blisters and bubbles
    - Fuel retention within the structure
- Recycling
    - Cold hydrogenic species
    - Impurity atoms
    - Secondary electron emission



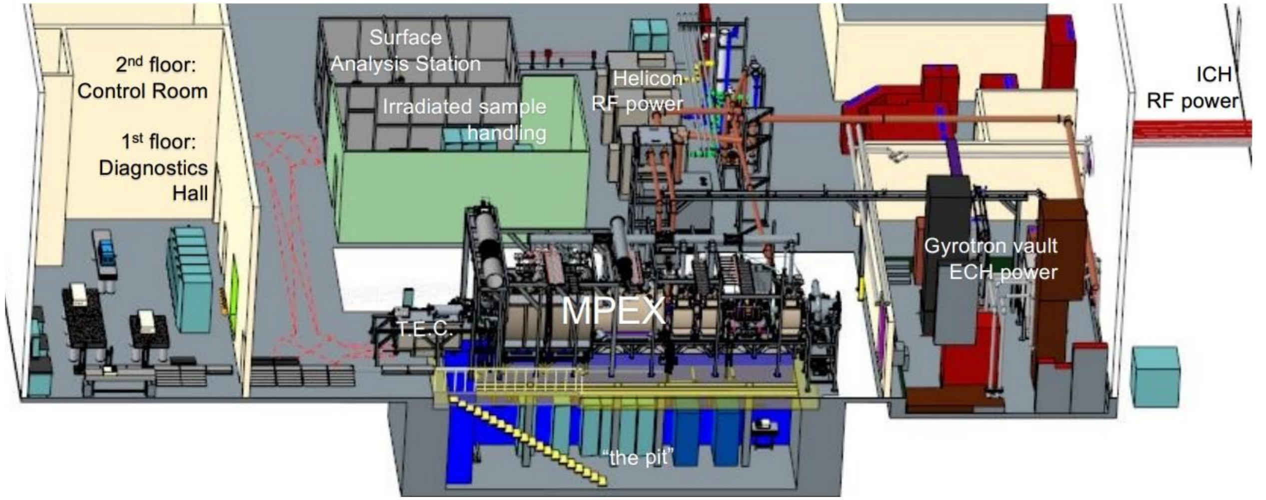
Consequences of using liquid lithium

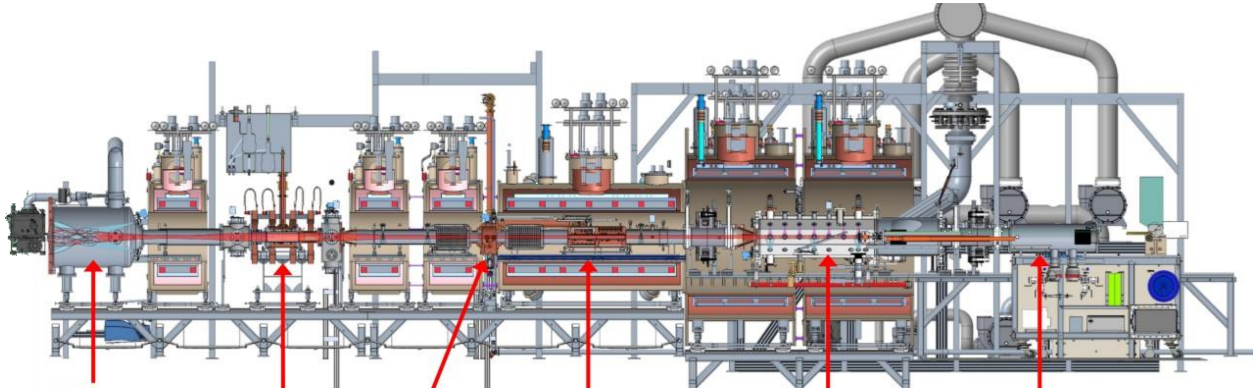
- **Known advantages**
    - Increased confinement time
        - Seen across the world
    - Higher temperatures and flattening of profiles
    - ELM suppression
    - Density control possible
    - Lower Z_{eff} (initially)
- **Potential other advantages**
    - Fuel retention
    - Helium pumping
    - Power handling (?)

D. Andruczyk et al., ITER Int. School 2019

Why use MPEX for these Studies? There is a need in the US to have a domestic, high heat and particle flux linear device for testing liquid metal concepts

	MPEX – ORNL	MAGNUM-PSI – DIFFER
Parameter	Aimed Value	
n_e source	up to 6×10^{19} m^{-3}	10^{21} m^{-3}
n_e target	up to 10^{21} m^{-3}	$10^{19} – 10^{21}$ m^{-3}
T_e source	up to 35 eV	
T_e target	down to 1 eV	0.1 – 10 eV
T_i source	up to 20 eV	
T_i target	down to 1 eV	1 eV
B_0 target	up to 1 T	Up to 2.5 T
d_0, Plasma Diameter	up to 10 cm	10 cm
Γ_1 target	10^{24} m^{-2}s^{-1}	$10^{23} – 10^{25}$ m^{-2}s^{-1}
Min angle of B to target	5 degrees	±90 degrees
P target, parallel	up to 40 MWm^{-2}	pulsed 2 GWm^{-2}
P target, perpendicular	10 MWm^{-2}	10 MWm^{-2}
t_{plasma}, pulse length	CW	CW





Dump Chamber plasma terminates upstream

Helicon Source 13.56 MHz 170 kW launched

EC Heating 70/105 GHz 400 kW launched

IC Heating 4-9 MHz 310 kW launched

PMI Chamber plasma terminates downstream

Target Exchange Chamber transports target

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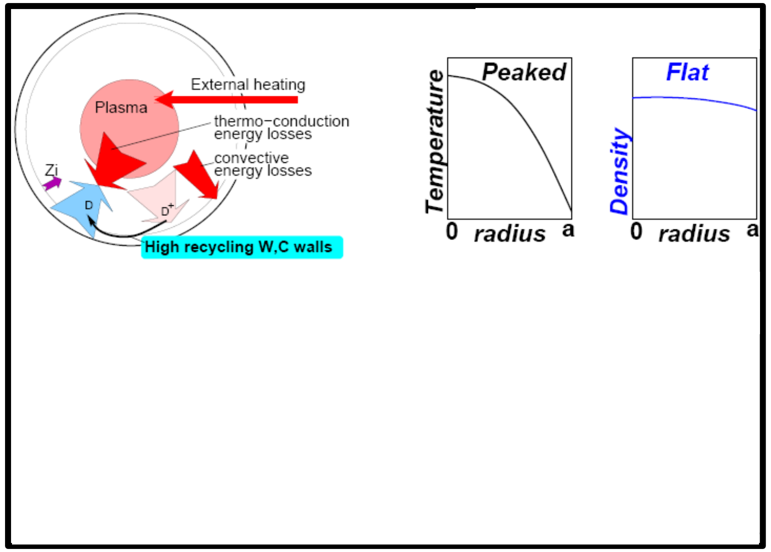
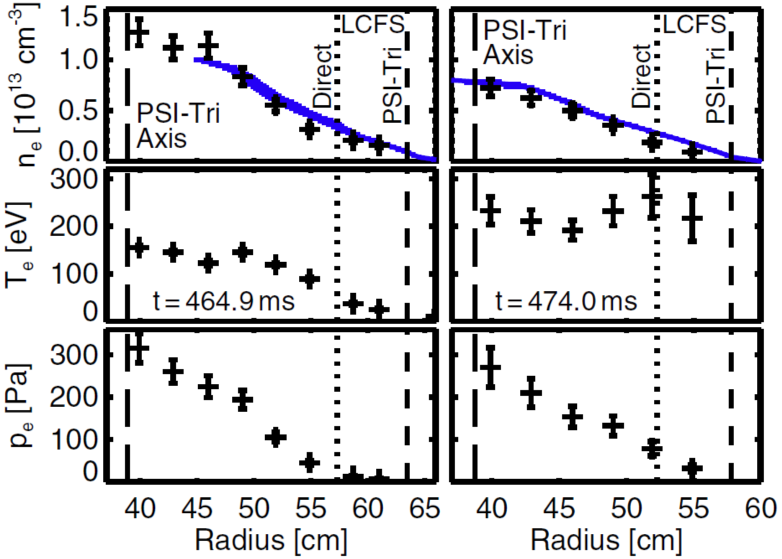
Questions that Need to be Answered - Recycling

- High recycling is the interaction of fuel ions (hydrogen) with the wall
  - Cold hydrogen returns from the wall – Plasma edge is cold
- Low recycling no cold hydrogen returns from the wall
  - Plasma stays hot



L. Zakharov Physics/ECE/NE Seminar (2008)

- Never comprehensively observed until recently in LTX
  - 60% of the hydrogen retained in the liquid metal walls
  - About a R = 0.4
- Density profiles slightly lower but also smooth out as expected.
- Radius needed is less than a high recycling machine
  - Volume and cost of fusion power reduced.



D. P. Boyle et al., Phys. Rev. Letter. 119 (2017) 015001

- **What is the impact on the plasma parameters with low recycling conditions and how does it extrapolate to a toroidal device?**

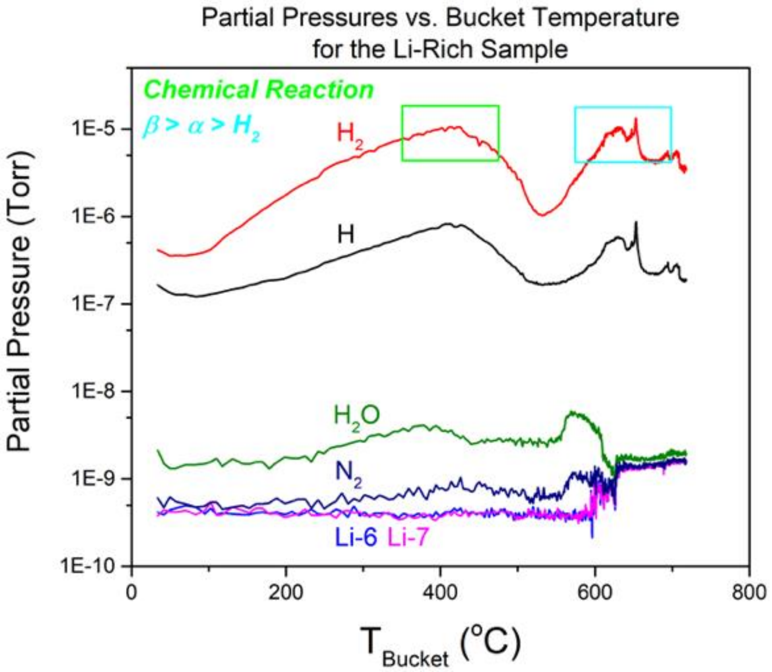
Question that Need to be Answered – H/D Pumping and Recovery

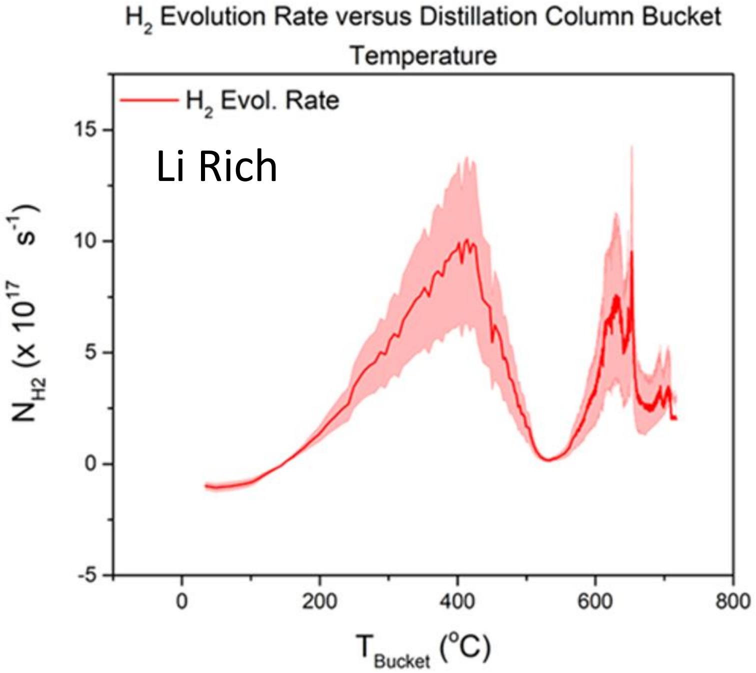
High H:Li Ratio Needed to Produce Relevant Evolution Rates

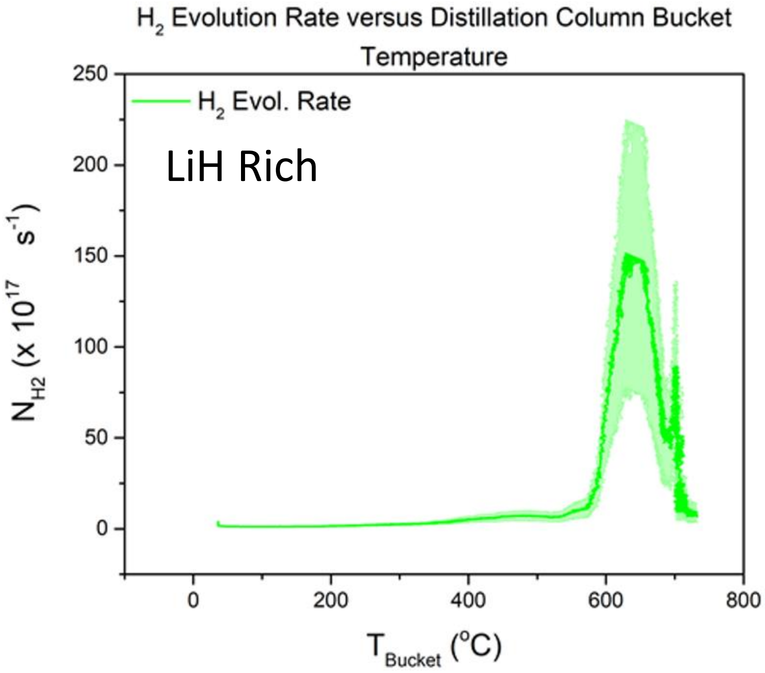
- Hydrogenic species (H, D, T) will be dissolved in Li or react to form LiH, LiD or LiT
  - Fuel losses
  - Need to be replaced or reused
- H_2 evolution occurs near melting temperature of 690 ^oC
- LiH rich melt needed to elevate the H_2 evolution to relevant values

- **Can hydrogenic species be removed by a flowing LM system and recovered in enough time to help with fueling a reactor**

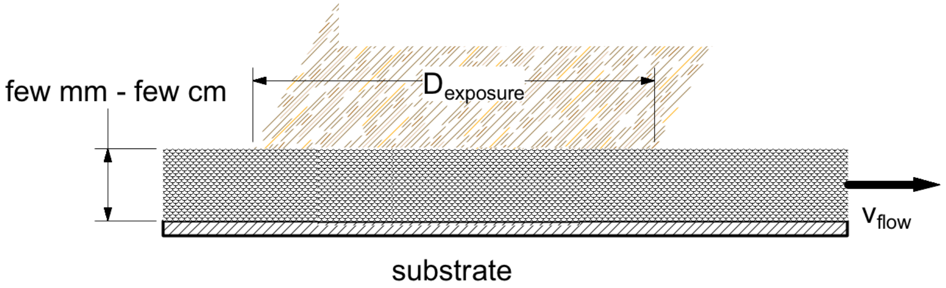
*M. Christenson et al., Fusion Eng. Design, **135** (2018) 81-87.*







Questions that need to be answered – He pumping, can it be done?



Particle Flux

1. **D/T Pump: D/T particles are likely be trapped in the LM surface (e.g., Li) due to the high chemical solubility of hydrogen**
2. **He Pump: Reasonable chance of adequate Helium self-trapping in flowing lithium as PFC without active pumping at 10-30 m/s**

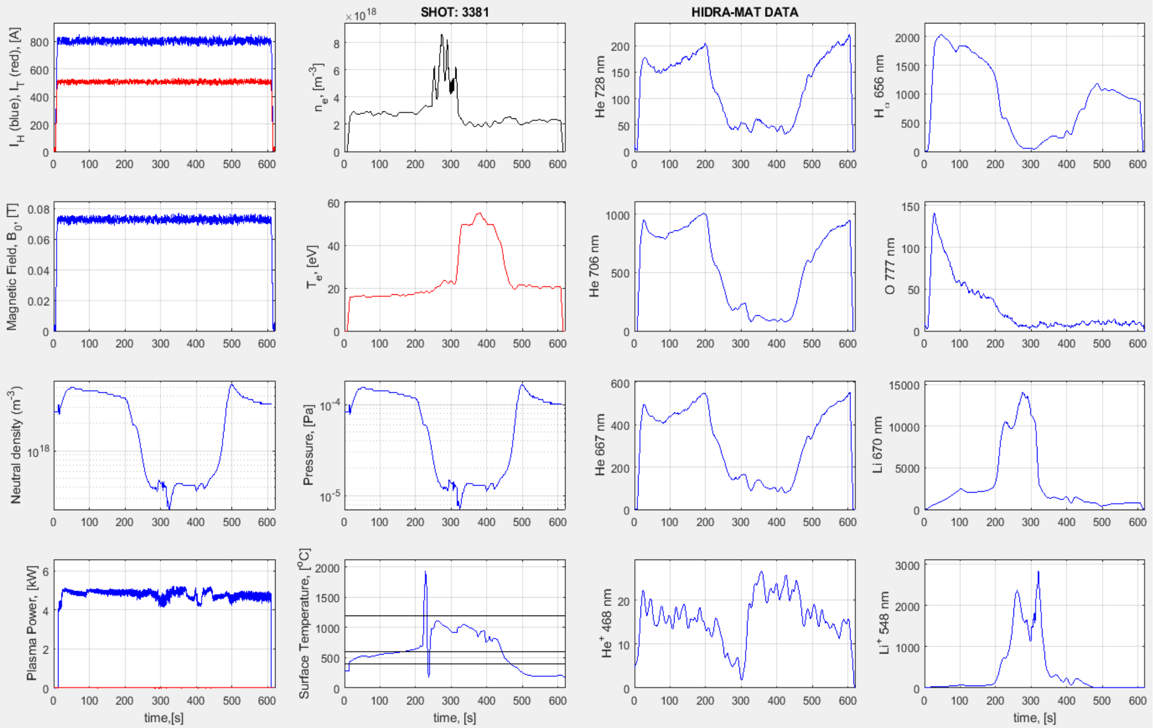
Hassanein, JNM 302 (2002) 41 + JNM 307 (2002) 1517–1519,Free Surface Flowing Liquid-Plasma Interaction Facility GRANT # DE-FG02-01ER86134, (Stubbers and G.H. Miley)

This might reduce/avoid requirement for reactor cryo pumping

➔ Smaller/cheaper reactor

> **"Helium is a headache for cryo pumps, as it hardly sticks to surfaces even as cold as four or five kelvin. KIT's vacuum experts spent years looking for the most efficient carbon structure to trap helium and finally settled for coconut charcoal from a certain patch of land in Indonesia.**

https://www.euro-fusion.org/newsletter/kit-completes-design-of-iter-cryo-pump/

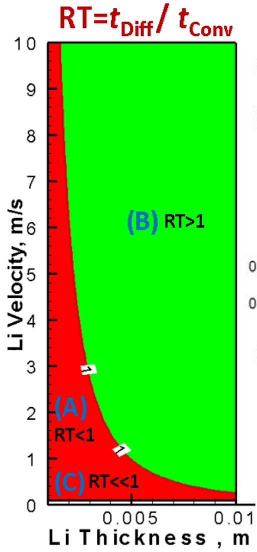


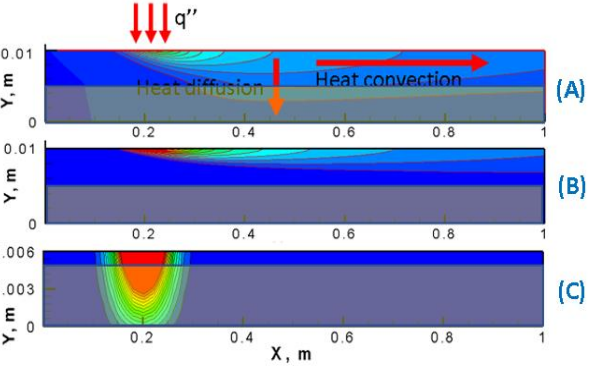
Long pulse expts. in HIDRA have shown the first potential evidence that Li will trap He and could lead to a pumping scheme for a liquid Li/He system.

D. Andruczyk et al., final draft under review before submission (2021)

Heat Flux Handling

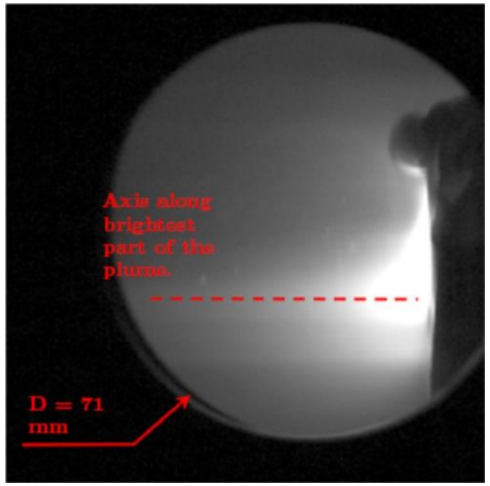
- **Can heat flux can be handled by a flowing lithium system**
    - High speed flows 1 – 10 m/s
    - Slow – medium flows are more for recycling control
- **Vapor shielding**
    - Spreading of the energy
    - Radiation
    - Changing local plasma properties
- **Engineered structures surfaces.**
    - 2D and 3D TEMHD based structured posts and meshes could potentially handle 10 MWm^{-2} or more





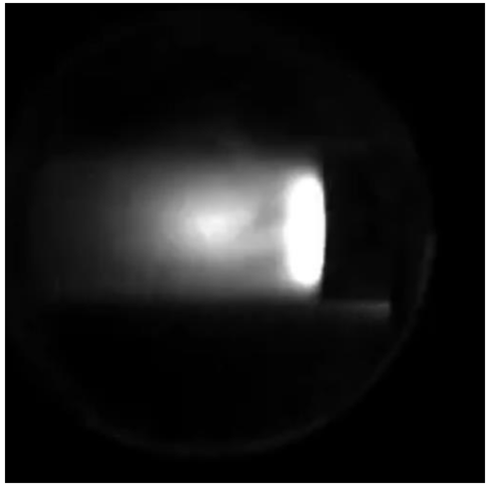
R. Maingi et al., EPS-DPP 2021

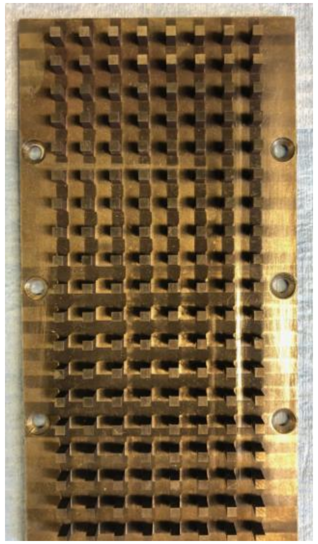
(A) Heat removed by Li and He
(B) Heat removed by only Li: 10 MW/m^2 @ 7 m/s, T_{surf} = 450 C°
(C) Heat removed by He ≤ 0.5 MW/m^2



P.Rindt et al., J. Nucl. Fusion 59 (2019) 056003

R. Rizkallah et al., APS-DPP (2020)





M. Szott PhD Thesis UIUC 2020

D. Andruczyk et al., TOFE 2020

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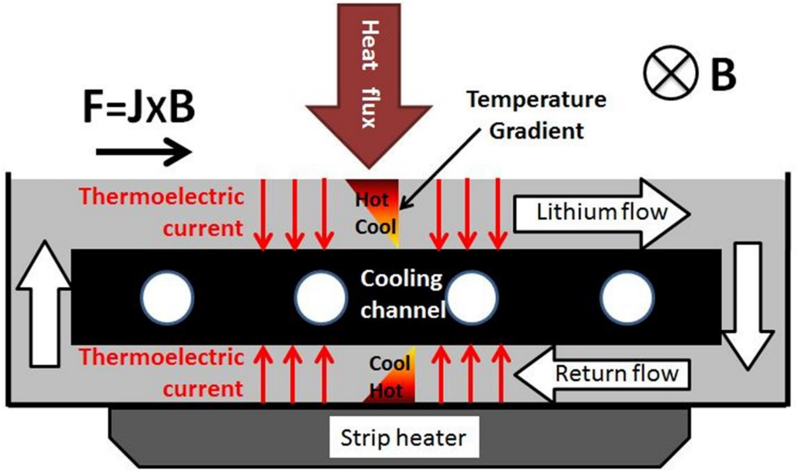
Liquid Metal Infused Trenches - LiMIT

Use What the Plasma Gives You!!!

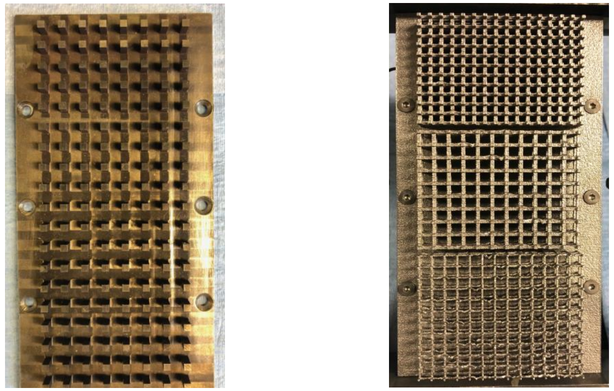
Thermo-electric Magnetohydrodynamics (TEMHD)

- Concepts for some heat removal and constant fresh lithium surface using TEMHD:
  - The Li flows in the slots of the metal plate powered by the vertical temperature gradient.
  - This vertical temperature gradient generates **vertical current**, which when "crossed" by the **toroidal magnetic field**, will create a **radial force on the Li driving it along the slot**.
  - This flow will transfer the heat from the strike point to other portions of the divertor plate.
  - The bulk of the metal plate could be actively cooled for a long-pulsed device or passively. Under the plate the Li flows back naturally.

- **Testing of new TEMHD concepts where simulations show can handle much higher heat fluxes. MPEX can provide the high heat flux to test these.**

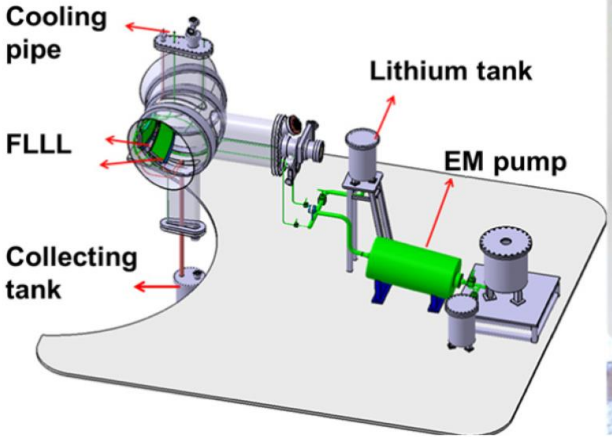


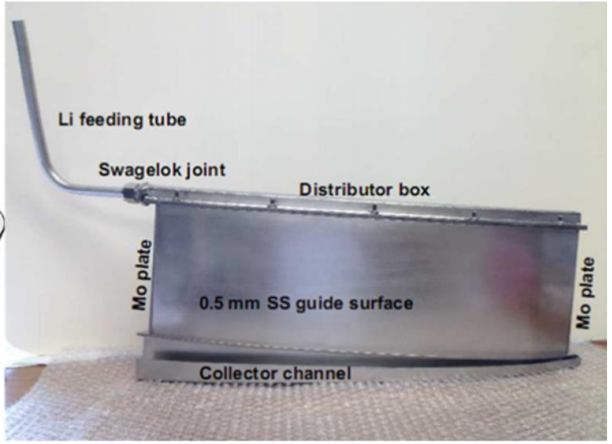
Ruzic et al., Nucl. Fusion 51 (2011) 012002



Flowing Liquid Lithium (FLiLi) Limiter

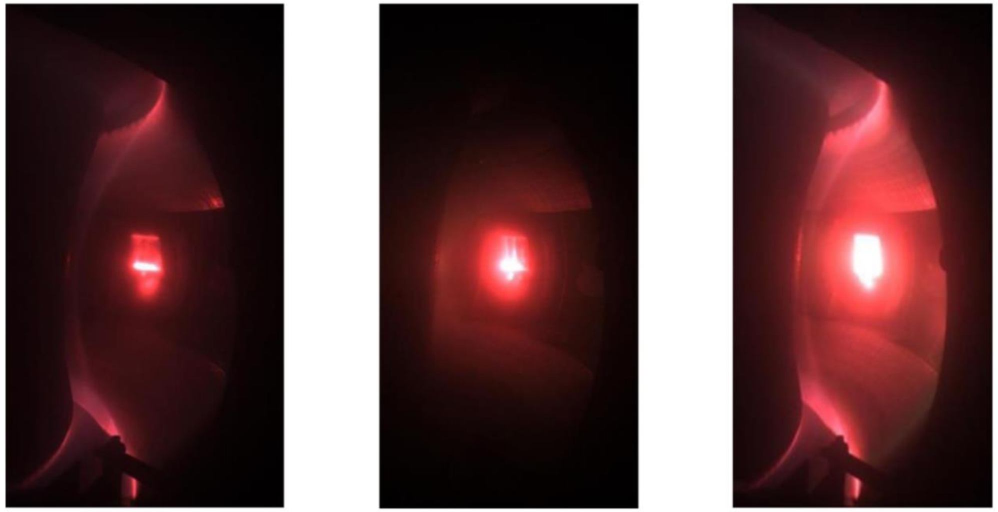
- FLiLi is a gravity based flowing lithium system
- Lithium flows down a flat plate. A distribution and collection reservoir keep the lithium circulating
    - MHD pump used for circulation
- First experiments were performed on HT-7 on its last run day
- Further experiments were continues on EAST



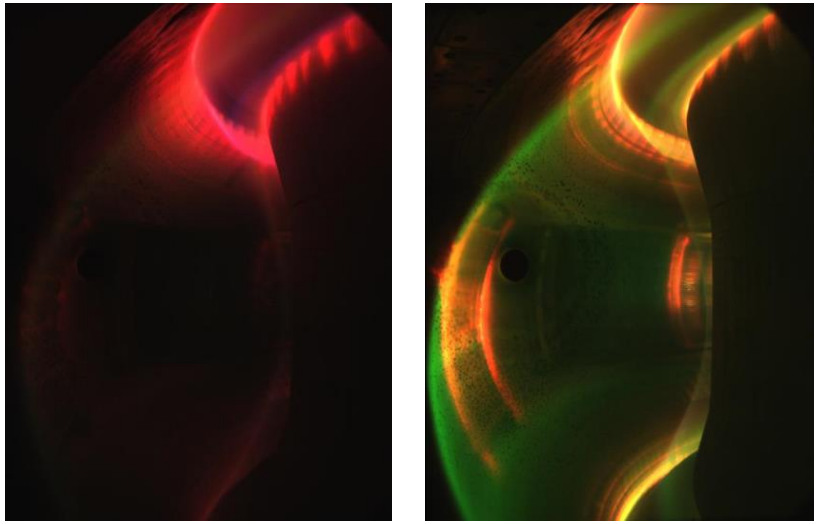


G. Z. Zuo, *et al.*, Phys. Plasmas 27, 052506 (2020); doi: 10.1063/1.5143179

- 3 generations of FLiLi plates have been tested
- **Further development:**
    - **Distribution**
    - **Collection**
    - **Wetting**
    - **Heat conduction and heat flux distribution**



(a) *(b)* *(c)*

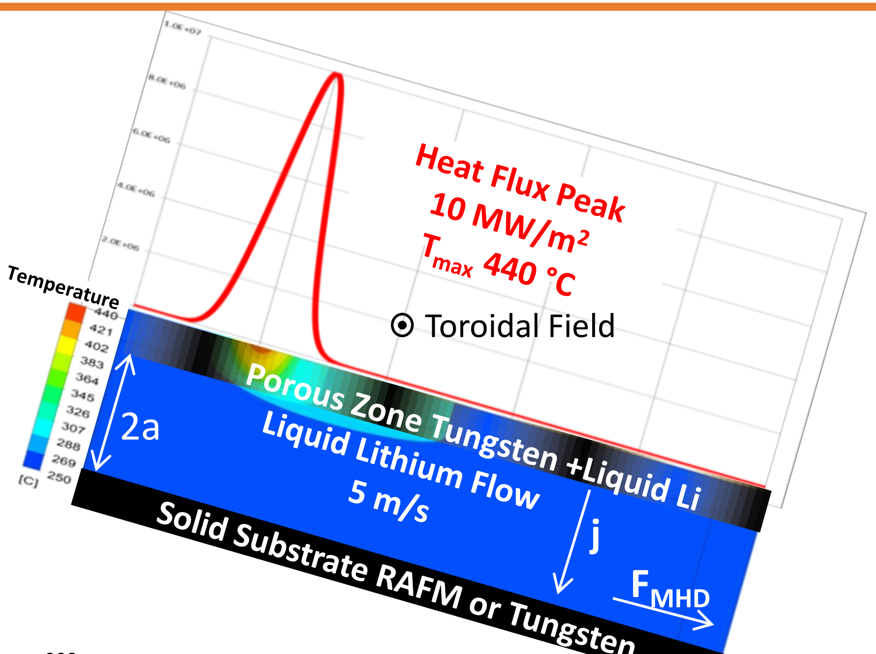


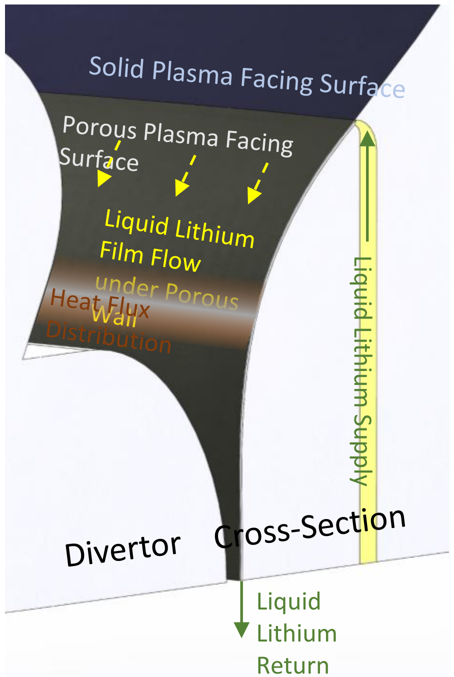
Without FLiLi With FLiLi

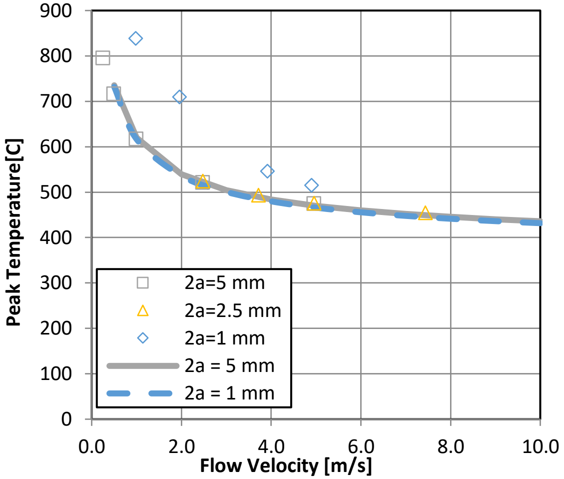
Liquid Metal Divertor Cooling System with Porous First Wall

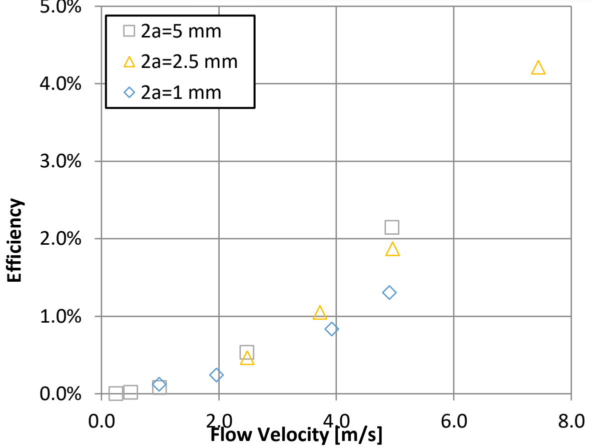
- The plasma-facing surface of the liquid metal (LM) cooling system is controlled by a solid, porous structure
    - The porous structure provides liquid Li on the plasma facing wall, allowing particle pumping in the case of low surface temperature liquid lithium, and evaporative cooling in the case of disruptions and ELM transients
- Flow velocity ≥ 7 m/s exhausts peak heat flux ≥ 10 MW/m²
- MHD pumping creates constant pressure condition in the LM, possibly creating a stable free surface on the porous media
- **Can a surface be cooled using a LM as the coolant**

A. Khodak *et al.* , Nuclear Materials and Energy (2021)
DOI: 10.1016/j.nme.2021.100935.

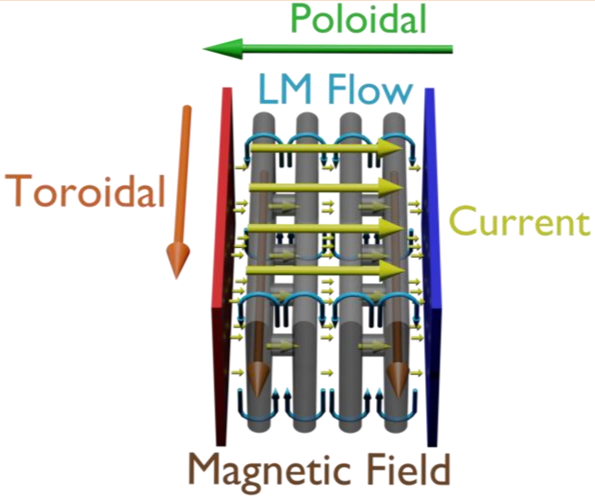




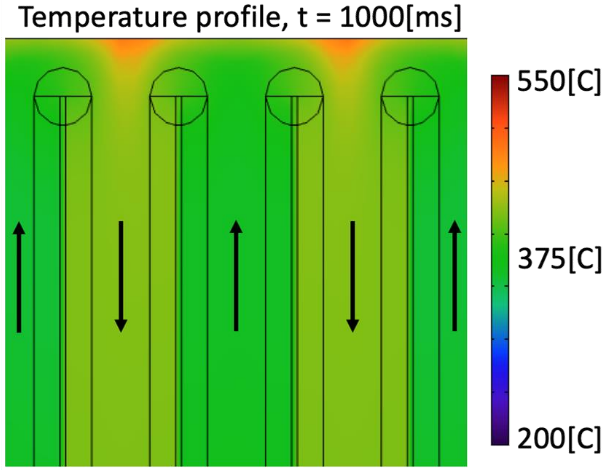




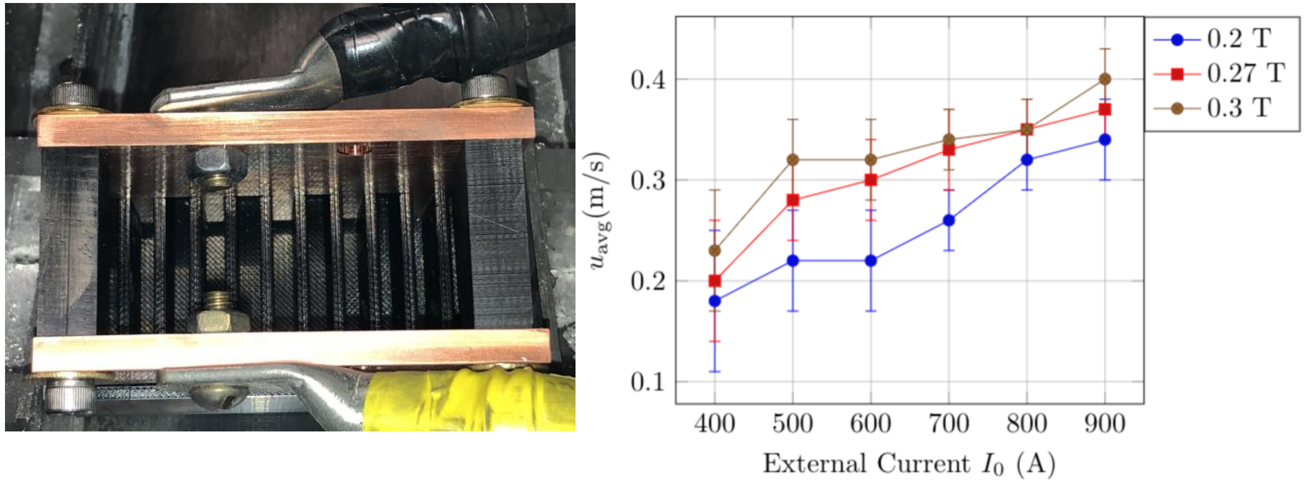
Divertorlets



Divertorlets Design



Achieve no evaporation (~20cm/s)



Divertorlets Experiments at LMX showing high speed flow.

- **Non-evaporating flowing Li divertor has many possible advantages:**
  - Heat Flux problem solved, high core confinement, D/T/He pum
- ***Issue:*** Need very high velocity (~10m/s) and high Li inventory
- ***Solution: "Divertolets"*** Cut the divertor into small regions (like radiator)
  - ↓ L➔ ↓ v (m/s ➔ cm/s)

$$v \approx 4Lq^2/(\Delta T^2 \pi k \rho c_p)$$

A. Fisher et al., Nucl. Mater. Energy 25 (2020) 100855

- Flow slowly with $\boldsymbol{j}\times\boldsymbol{B}$ only:
  - Reduce drag,
  - reduce splashing
- **Possible to use simpler flowing setups (1 lead, single piece divertorlet w/t no moving parts!)**

Li H/D/He separation – Magnetic Centrifuge

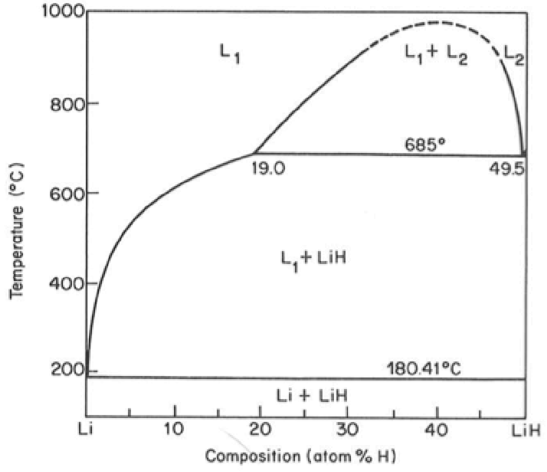
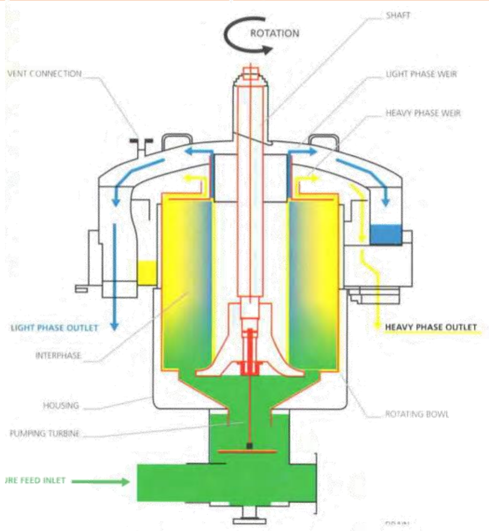
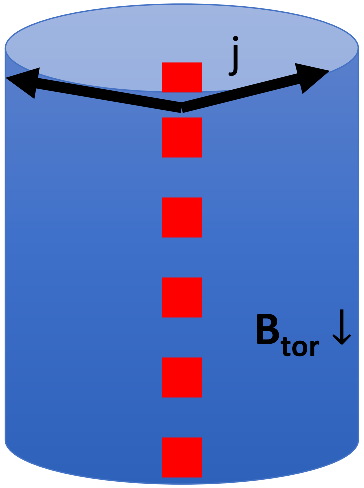
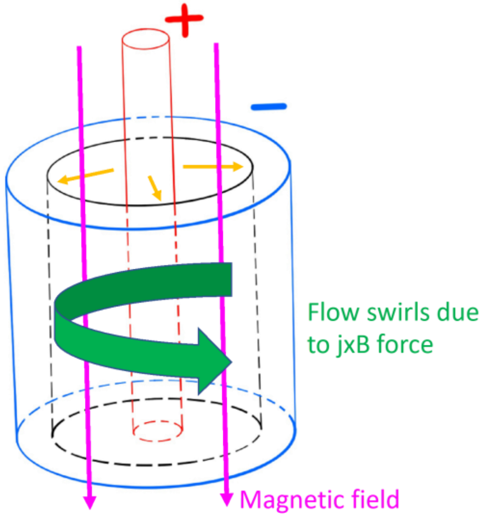


Figure 5.3 Lithium–lithium hydride phase diagram





Magnetic centrifuge



- **How to reduce Li inventory and pumping power? ➔**
  - 1) Keep Lithium in Tokamak high field region
  - 2) Just take LiD outside!
- **Method:** Solubility of hydrogen in lithium falls rapidly with temperature
  - 0.3 At. % at 300 °C ➪ 0.044% at 200 °C. ➔ LiD, LiT will be formed
- Density of LiT (1.0 g/cm^3), LiD (0.9 g/cm^3) *twice* liquid lithium (0.5 g/cm^3)
- Separation via magnetic centrifuge (We have B in tokamak, need to run j in a cylinder)
  - Centrifuges would operate at ~190°C ➔ Enriched slurry of LiD, LiT removed continuously at periphery
- **Flow to tritium separation unit (miniscule) ↓ (i.e. Low Li inventorty needed) ➔ MHD drag ↓ ➔ Power ↓**

- **Demonstrate the magnetic centrifuge using MPEX magnetic fields. Can the LiD be enriched and seerated out?**

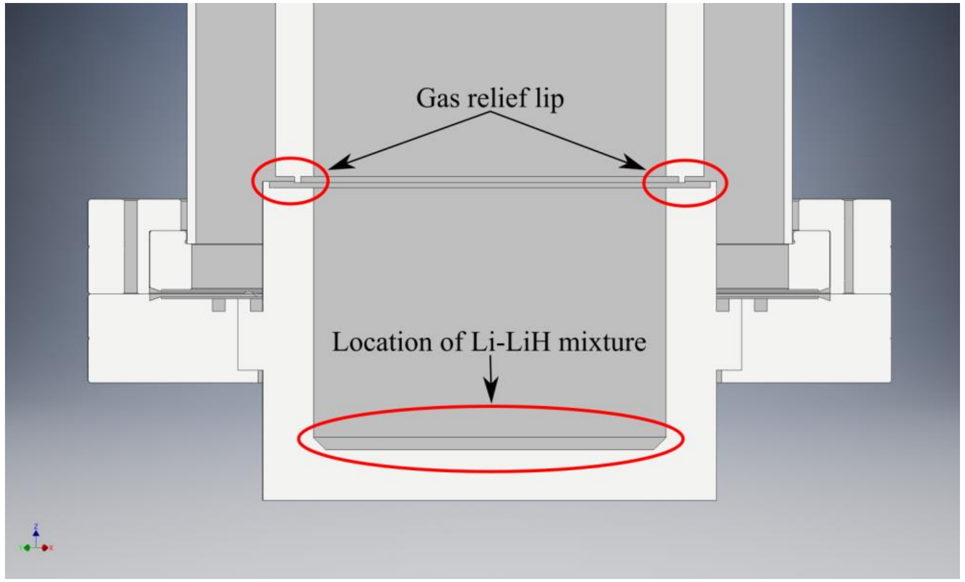
Distillation Column

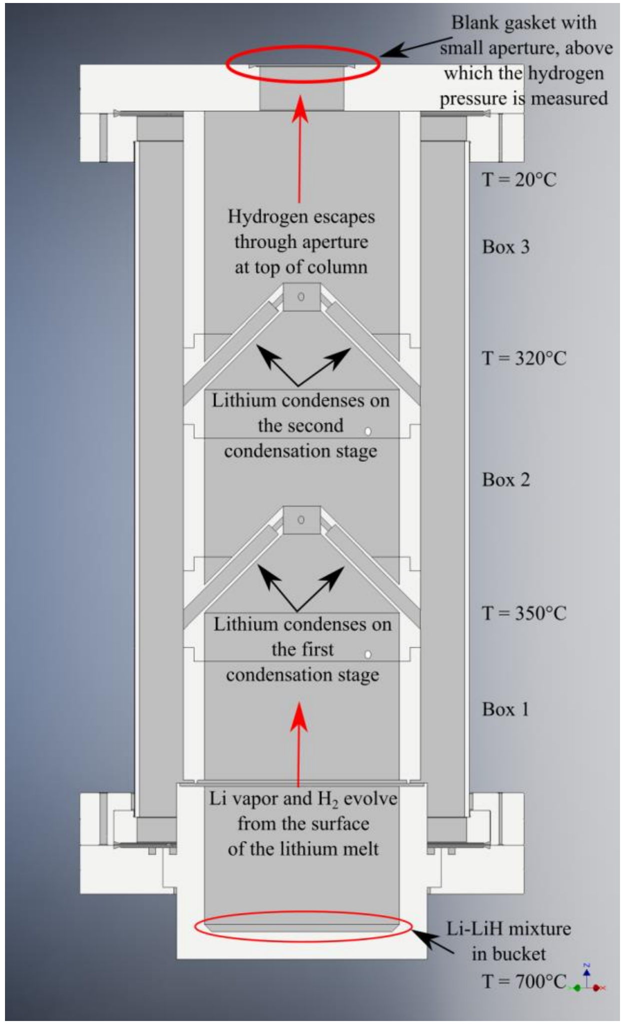
Distillation Column Designed for Hydrogen Isotope Removal from Lithium Melts

- High hydrogen isotope retention in lithium plasma-facing components
- Lithium and hydrogen separation with distillation column
- Condense lithium on stages

M. Christenson et al., Fusion Eng. Design, ***135*** *(2018) 81-87.*

- Allow gas to escape out the top of the column
- RGA used to determine evolution rates
- Will need to be Part of an overall back-end solution
- **Demonstrate successful operation of a distillation system with a LM PFC surface.**





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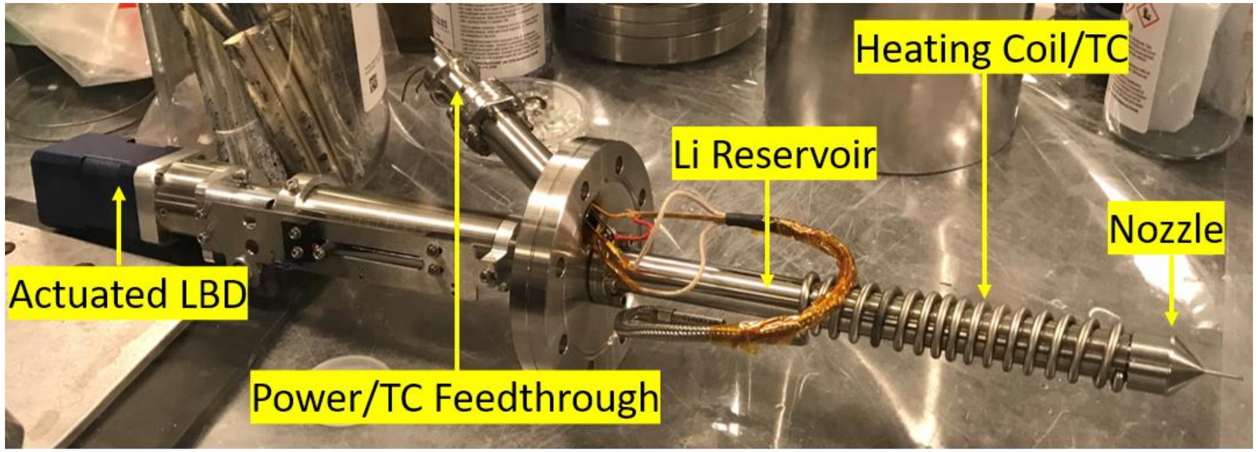
LM and Li Needs for MPEX

- Glove Box (stationary or mobile?)
  - Ensure Li handling is done in as pure of an environment as possible
  - No exposure to air
  - Needed for being able to track hydrogen.
- Lithium Loop
  - External Li loop, similar to what is being built for TE and MEME at UIUC
  - Or internal loop, similar to the one in FLiLi on EAST
- Li Injection system?
  - If there us no loop system, so we have a Li injection system for loading Li into the surfaces?
- Post experiment facility
  - Removing lithium and LM from components and reuse
    - Water or Acetic acid bath, gas removal
    - Baking and cleaning, preparation of reusable systems.
- Lithium inventory
  - How much lithium can we have?
    - MPEX in vessel, 3.25 moles (25g) surface flow
    - What are the total building limits?
      - ***National Fire Protection Agency (NFPA) 484 - alkali metals Code***
      - 0.5 lbs. (227 g) for a mixed building with offices
      - With other protections and safeguards can be between 5 -50 lbs.



LM and Li Needs for MPEX

Diagnostics

- There will be a need for a great number of diagnostics, not just for the liquid metal systems but also for the plasma systems to know how its affected by lithium
- Liquid Metal Diagnostics
  - Flow meters
  - IR Camera
  - Thermocouples
- Plasma / Vacuum Diagnostics
  - Pressure Gauges
  - Residual Gas analyzers (RGA)
  - Spectroscopy
  - Visible Camera (with filters)

Outline

- Background
  - Why interest in liquid lithium/metal research
  - Why MPEX?
- Questions that need to be asked/answered
  - Recycling
  - Pumping and Recovery of H/D (T surrogate)
  - Helium Pumping, can it be done?
  - Heat flux handling
- Flowing LM Concepts
  - LiMIT
  - FLiLi
  - Flowing Porous System
  - Divertolets
  - LiH Separation – Magnetic Centrifuge
  - Distillation Column
- What would be needed for MPEX
  - Lithium handling and flow systems
    - Glove Box (stationary and mobile)
    - Lithium Loop
    - Li Injection system?
    - Lithium inventory
  - Plasma Diagnostics
- Conclusion

Summary / Conclusion

- Liquid metal and lithium program on MPEX will be invaluable to further answer questions surrounding lithium’s ability to be a plasma facing material.
    - Heat flux handling
    - Recycling control
    - H/D/He handling and extraction
- The need for a long pulse / steady state device with high heat flux where liquid metal systems can be tested is needed.
    - The need for such a domestic system is clear
- The reality is that a dedicated LM / LLi schedule will be needed, probably towards the end of a run campaign
- There will be a need for dedicated LM facilities that attach to or a permanently part of MPEX
    - Glovebox
    - LM loop
    - LM injector
    - Post processing facilities
    - Diagnostics

Back Up Slides

Lithium exposure to water leak in MPEX PMI chamber

- Worst case:
  - Water leak onto hot solid target will result in strong reaction,
  - but mass is limited, so will self extinguish once metal is consumed.
  - steam + aerosol + hydrogen evolution.
- **5g Li** -> 0.73g H,
  - That would bring 17.6 liters to 1 atm @ RT
- PMI chamber is 0.477 m^3, (477 liters)
  - 136.3 g Li yields 1 atm H2
- **24 g (3.45 moles)** Li can generate enough hydrogen that when combined with air can exceed the lower explosive limit in the PMI chamber.

Potential Budget for a LM system for MPEX

Glove Box	$ 40k	IR Camera	$ 50k
Liquid Li Loop	$ 50k	Visible Camera	$ 50k
Distillation Column	$ 50k	Optical Filters	$ 5k
Lithium Injector	$ 30k	Pressure Gauges	$ 10k
Liquid Li Technologies	$ 60k	Spectrometer	$ 30k
Li Inventory	$ 20k	RGAs	$ 10k
Cleaning Facility	$ 40k	Thermocouples	$ 5k
Other	$100k	Flow Meters	$ 50k

Estimated Total $600k

Other annual expenses $200k