# Liquid metal PFC designs for fusion devices

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on behalf of the U.S. domestic design team:

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**NSTX-U / Magnetic Fusion Science Meeting**

**9 Jan 2023**

# A domestic program has identified Liquid Metal PFC design windows for a Fusion Nuclear Science Facility (FNSF)



- **Goal**: design LM PFC concepts for a nuclear device, i.e. **FNSF** or FPP
- **Choices**: analyze 1) Li, 2) divertor, 3) flowing PFCs
- **Design issues**: MHD flow instabilities, Li pumping through magnetic field, plasma/material interactions, corrosion/erosion/embrittlement, ….

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- Self-consistent between LM MHD, heat transfer and plasma modeling
- Required Li PFC flow speeds ~ 5-15 m/s
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- **Experiments** for model validation and to test material and flow properties conducted in test stands and linear flow experiments with applied B

➢ NSTX-U Liquid Li PFC designs use concepts developed in the FNSF design

# Solids are the leading options for plasma-facing components Tungsten chosen for the divertor & Be for the wall of ITER

- Tungsten (W) advantages
  - Low physical sputtering yield; high threshold
  - No chemical sputtering with hydrogen
  - Low in-vessel tritium retention at T < 500 $^{o}$C
  - Reparable by plasma spray; good joining technology

- W disadvantages
  - Low allowable core concentration
  - Melts under large transient loads
  - High ductile-brittle transition temperature
  - Recrystallizes (embrittles) at temperatures >1500 K
  - High activation
  - Blisters and generates ‘fuzz’ under He bombardment



G. Federici, et. al., Nucl. Fusion **41** (2001) 1967

# Liquid metal PFCs may be an attractive option to solid PFCs, but have substantial R&D needs to assess viability



- Advantages
  - Erosion tolerable from PFC view: self-healing surface
  - No dust; main chamber material and tritium transported to divertor could be removed via flow outside of tokamak
  - Liquid metal is neutron tolerant; protects substrate from PMI
  - Liquid (and solid) lithium offer access to low recycling, high confinement regimes under proper conditions
  - Very high steady, and transient heat exhaust, in principle (50 $MW/m^2$ from electron beam exhausted; also 60 $MJ/m^2$ in 1 $\mu$sec)
- Disadvantages and R&D needs
  - Liquid metal surfaces and flows need to be stable
  - Liquid metal chemistry needs to be controlled
  - Temperature windows need optimization

* Most of experience in the US is with Li, but Sn and eutectics (e.g. Sn-Li) offer some promise in terms of broader temperature windows

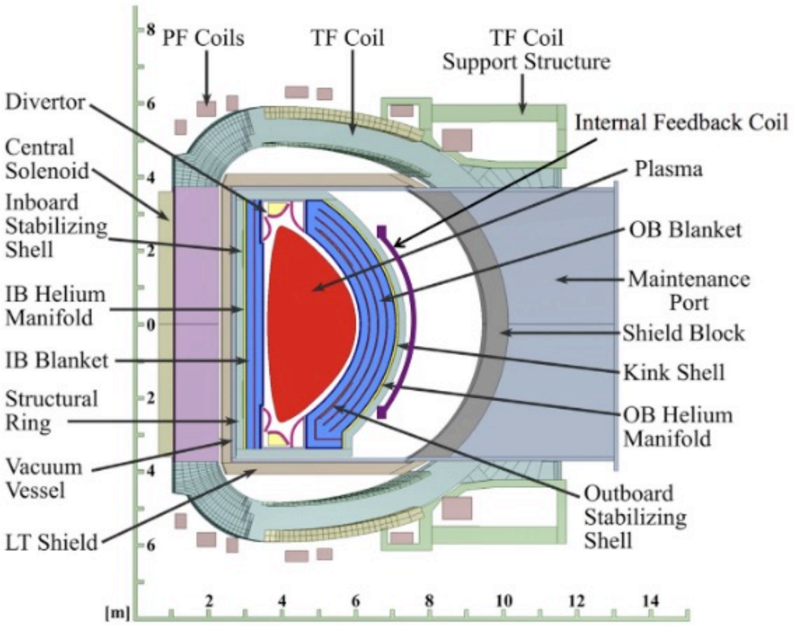
# Fusion Nuclear Science Facility aims to qualify materials and PC designs for fusion applications



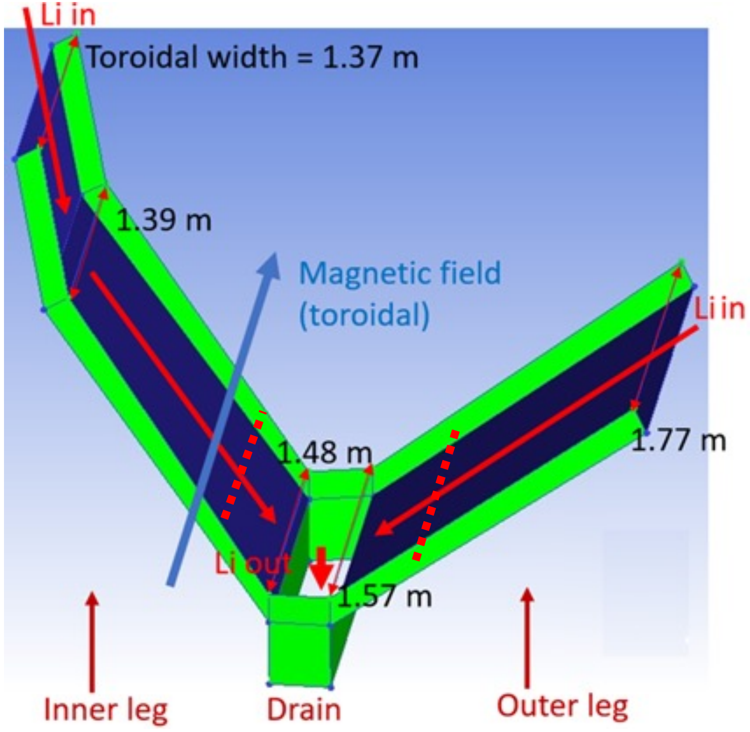
**FNSF - Tokamak-based machine with ~520 MW fusion power:**

- 4.8-m major radius, 1.2-m minor radius
- Average neutron wall loading ~ 1 $MW/m^2$, divertor heat flux ~ 10 $MW/m^2$

C.E. Kessel et al. / Fusion Engineering and Design 135 (2018) 236–270

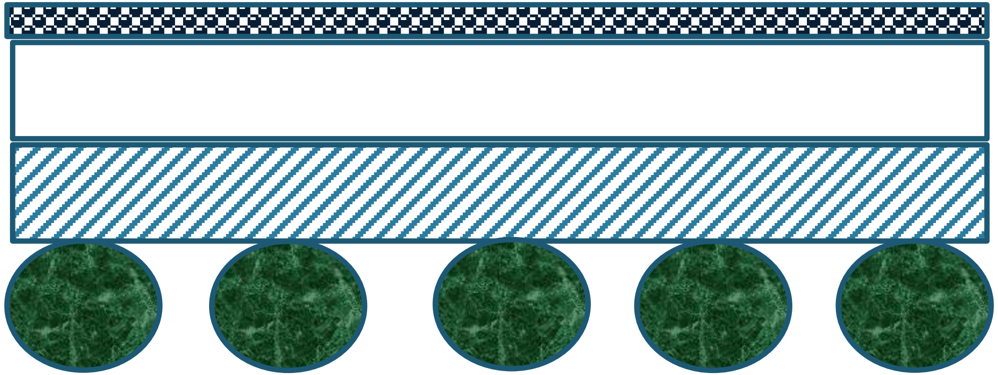



The cross-section of the FNSF, identifying the various components in and near the fusion core.

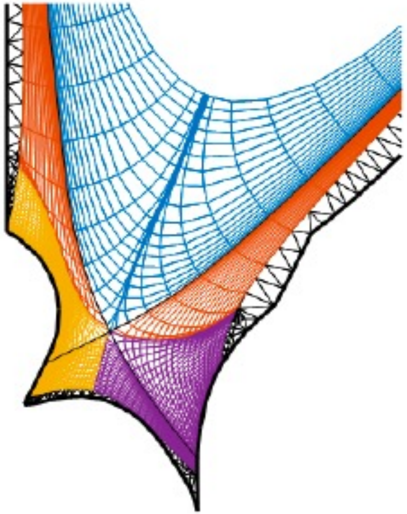


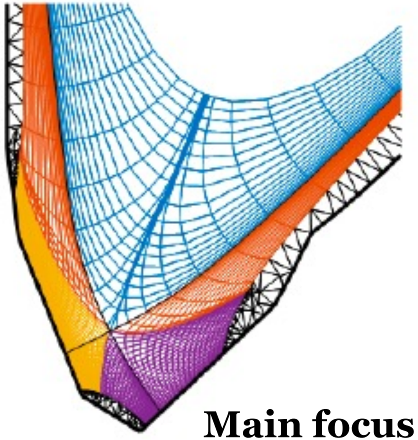
# We consider a general liquid metal PFC design

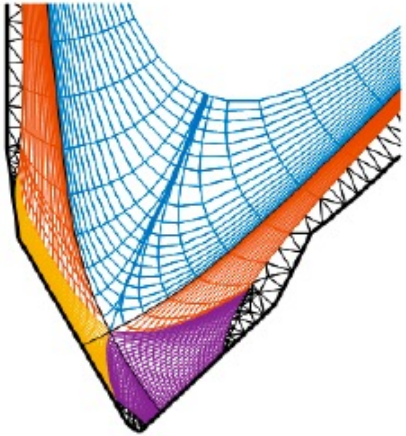
- **Design calculations: 10 MW/m² input peak heat flux on a flowing divertor PFC, with different profile shapes**

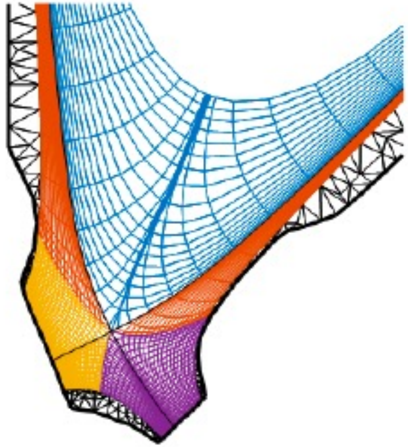


# Several boundary/PFC designs being evaluated







**"ITER-like" baffled vertical target divertor**

- Reduces deposited fluxes via tilted target in poloidal plane
- Neutrals are preferentially recycled/reflected towards dissipation zones

**"2-leg" and "3-leg" [2] simplified divertors**

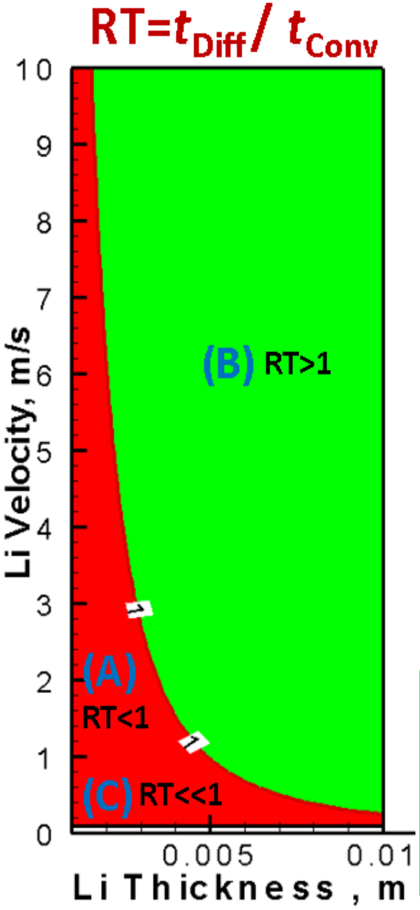
- Plasma facing surfaces are planar in the poloidal plane
- Increased deposited fluxes due to nearly perpendicular angle to separatrix in poloidal plane
- Little control of neutrals

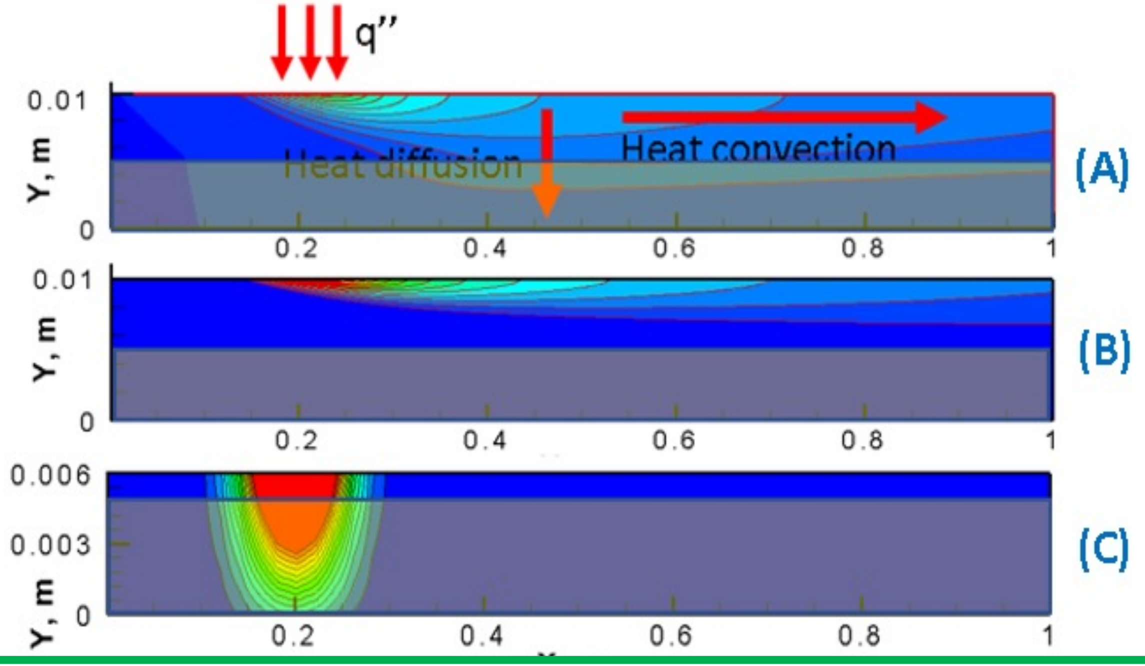
**Balanced divertor with baffling and simplified targets**

- Length of divertor legs increased with close baffling for neutral control
- Simple geometry in plasma wetted areas to facilitate LM designs

J.D. Lore et al., IEEE TPS **50** (2022) 4199

# Free surface MHD calculations identify several power exhaust regimes



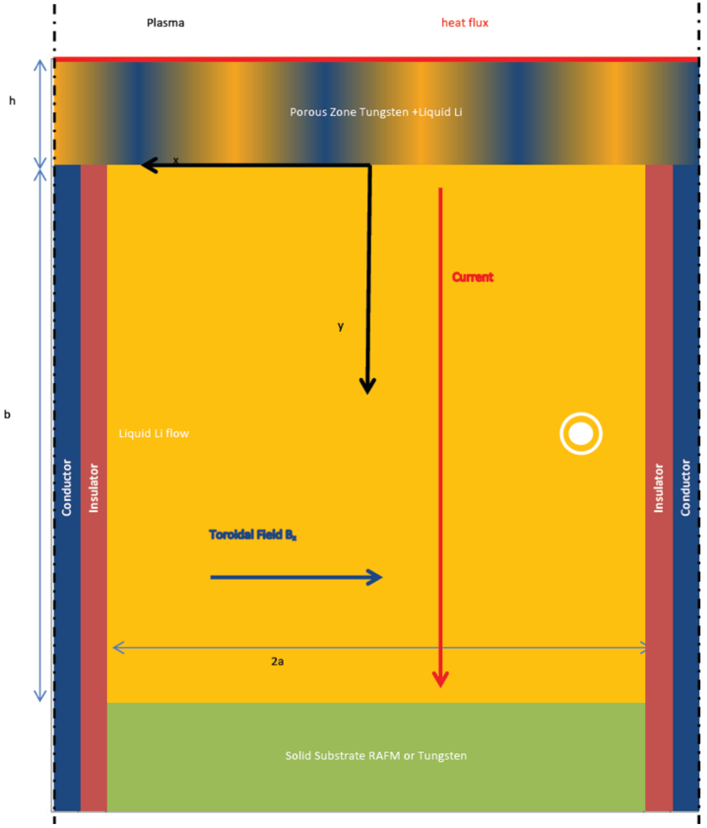

(A) Heat removed by Li and He

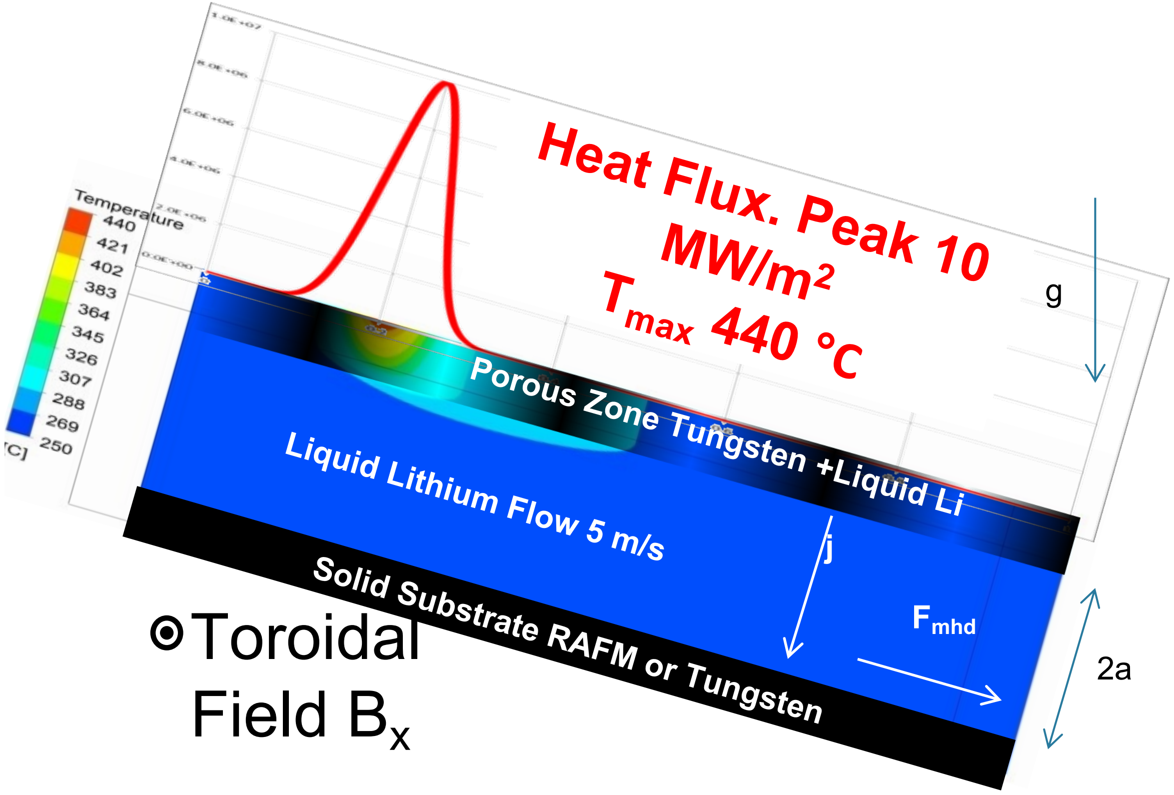
(B) Heat removed by only Li: 10 MW/m$^2$ @ 7 m/s, $T_{surf}$ = 450 C$^o$

(C) Heat removed by He $\leq$ 0.5 MW/m$^2$

S. Smolentsev, **FED** *173* (2021) 112930

# Capillary porous system with j x B drive can exhaust required heat flux

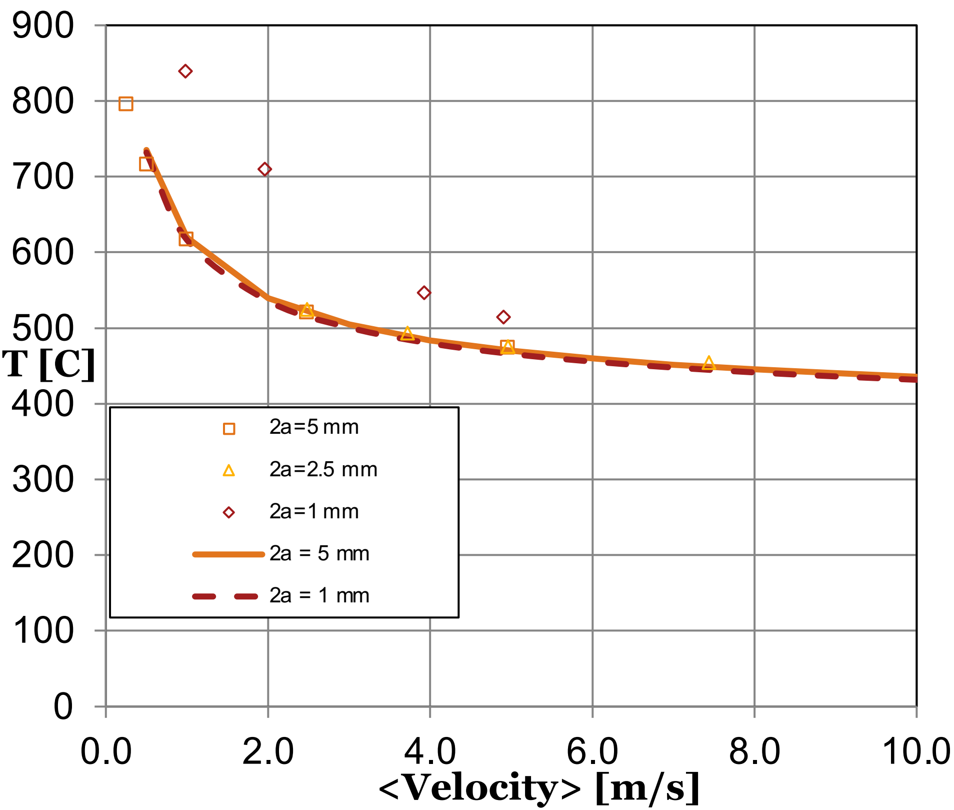


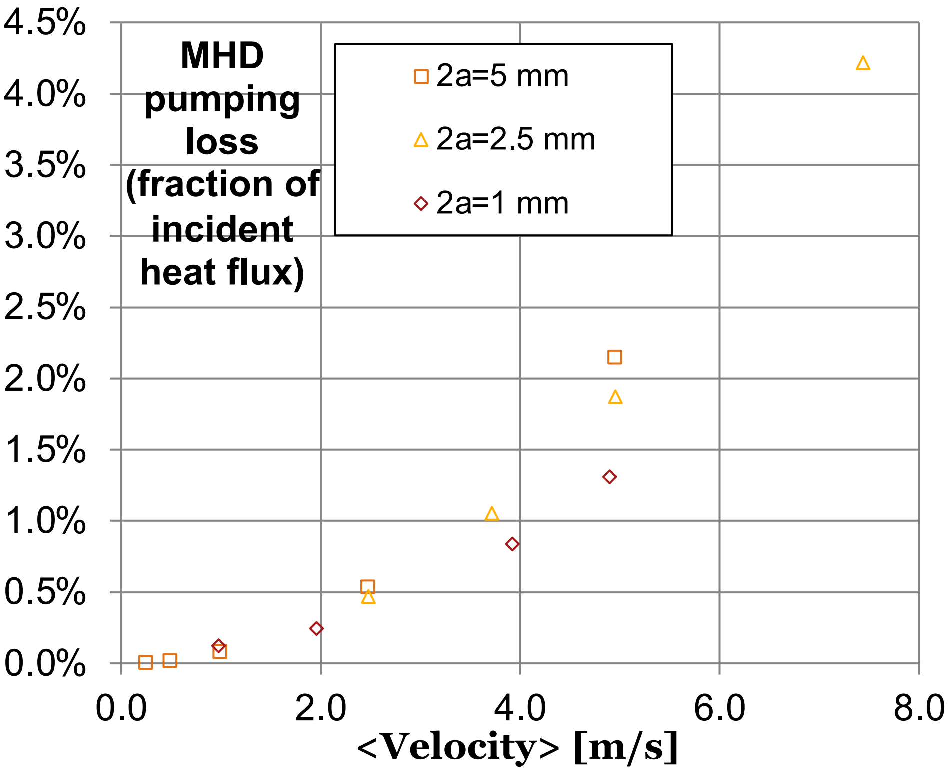




A. Khodak and R. Maingi, *NME* **26** (2021) 100935

# CPS can exhaust 10 MW/m² with 7 m/s flow and < 10% of incident heat flux



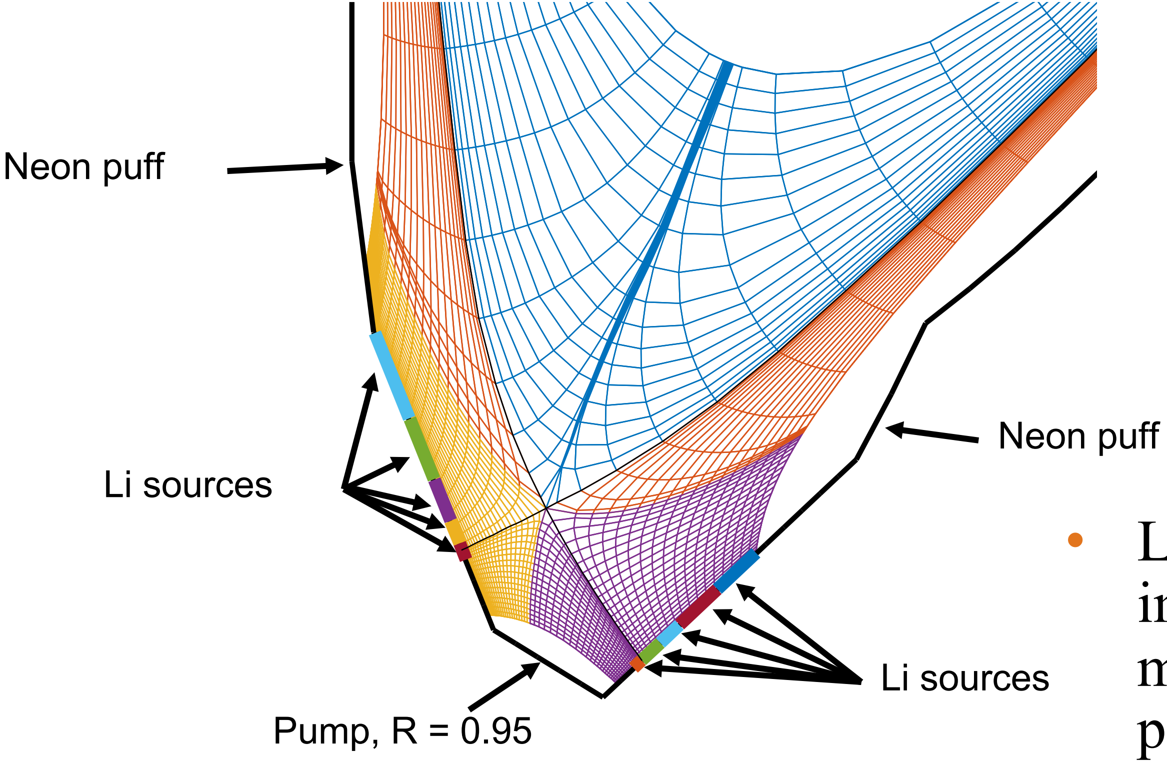



A. Khodak and R. Maingi, *NME* **26** (2021) 100935

# Plasma response calculations with SOLPS-ITER inject Ne and Li in three-plate FNSF geometry



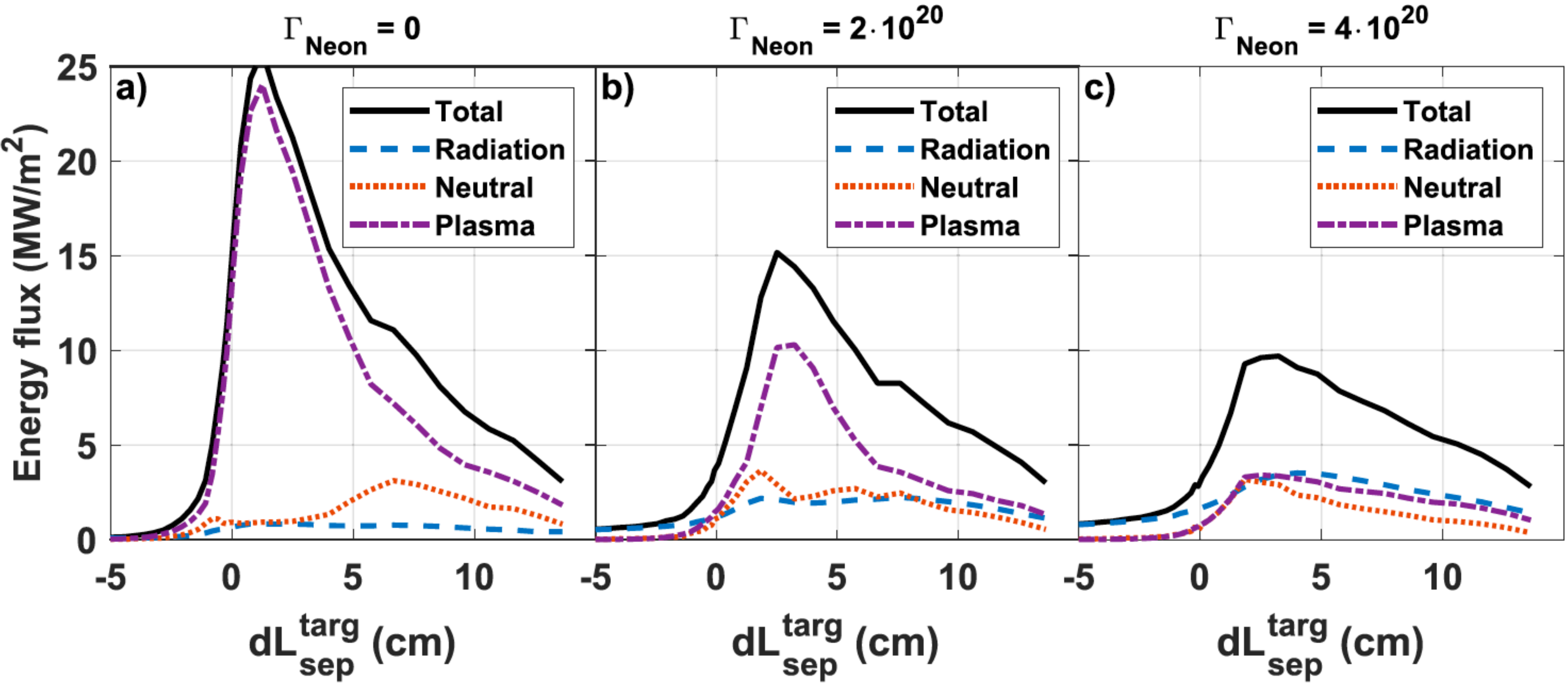



- Li sources based on improved evaporation model from UIUC, plus adatom models…

J.D. Lore et al., IEEE TPS **50** (2022) 4199

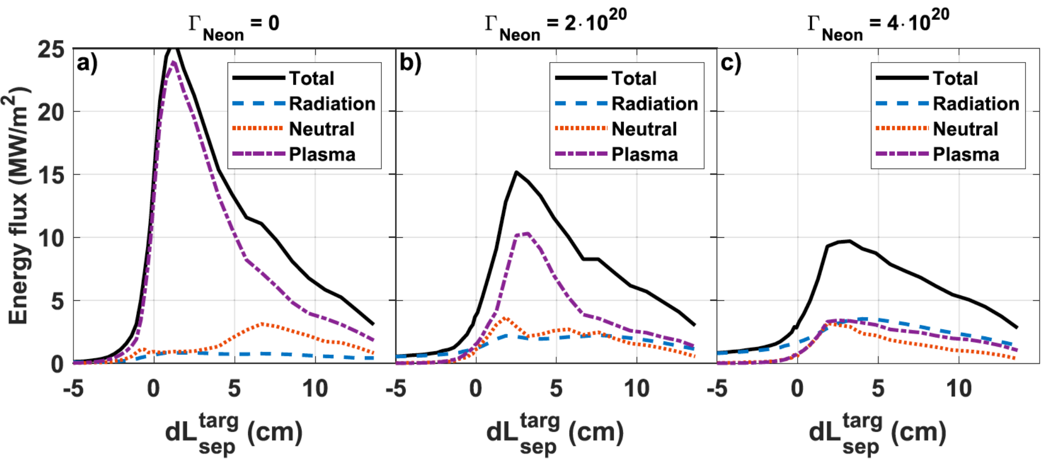
# SOLPS modeling: Heat flux reduced to < 10 MW/m² with Ne gas puffing

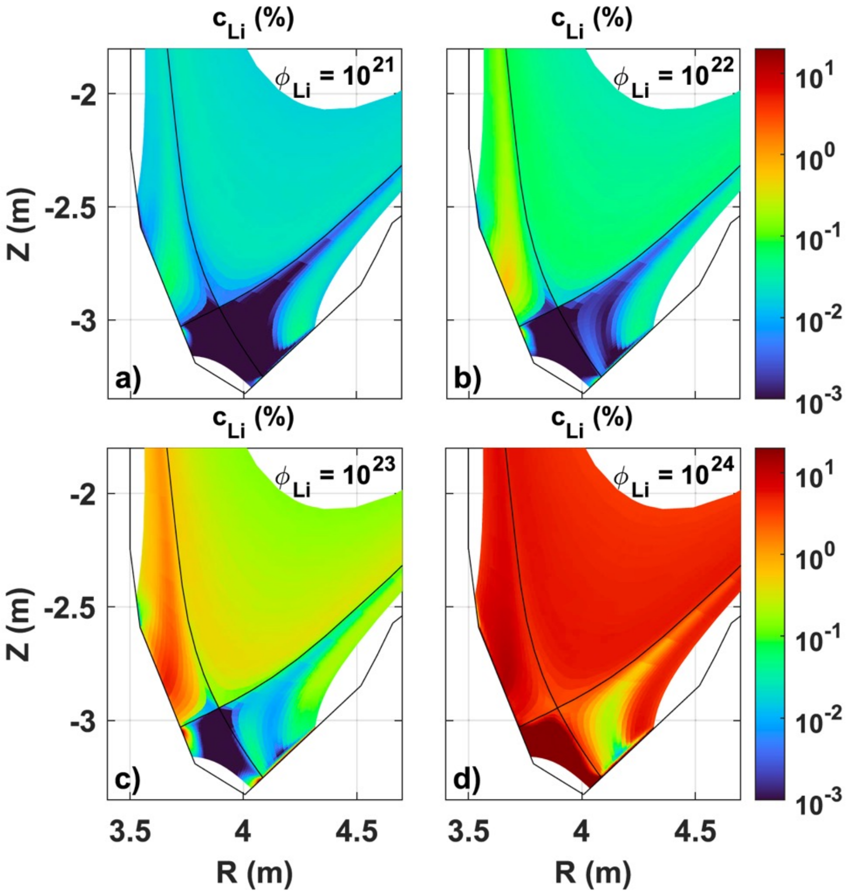





J.D. Lore et al., IEEE TPS **50** (2022) 4199

# SOLPS modeling: Heat flux reduced to < 10 MW/m² with very little Li leakage into the core




J.D. Lore et al., IEEE TPS **50** (2022) 4199

# LM PFC designs based on a US program that has identified LM PFC design windows for a Fusion Nuclear Science Facility (FNSF)



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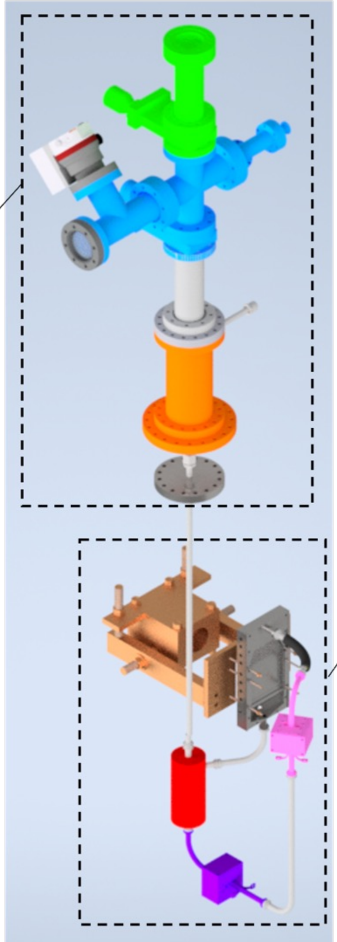
# Experiments at UIUC include large vacuum test stand with Li flow loops; fill systems; corrosion tests

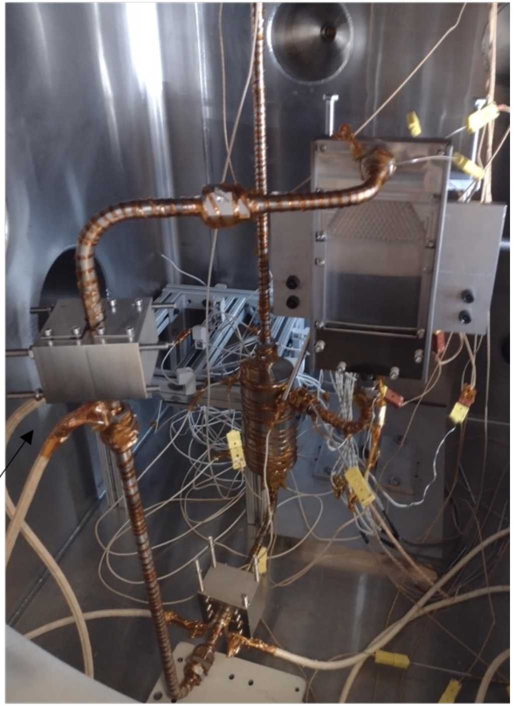


- Goal: develop new distribution systems for Li PFCs
- Study corrosion & erosion in flowing Li PFCs
- Li loader and loop system inserted in the MEME chamber

External Lithium Loader



Internal Lithium Loop



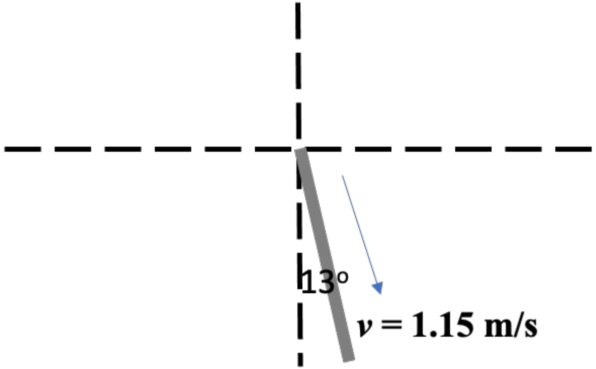
D. O'Dea, SOFE 2021

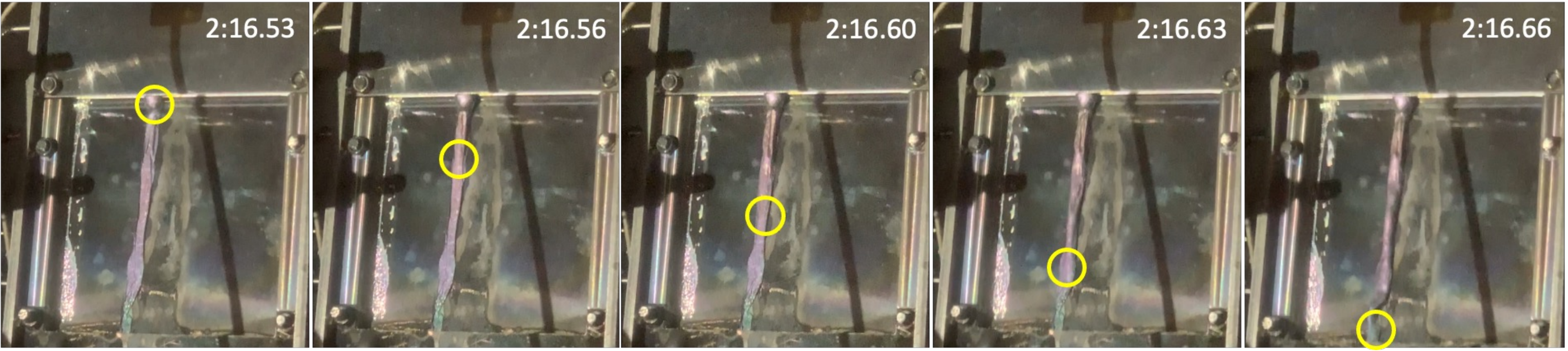
# Results of the Flowing liquid lithium loop in MEME

- Plate at 13.5° from the normal
- 15 cm length
- With 100 A into the EM pump get a velocity of

$$v = 1 \text{ m/s}$$

- Need to fix a design feature in the plate distributor
  - A gap between the posts and plate allows the Li to flow down the plate rather than wick into the posts
  - See an initial flow of Li down the edge of plate and good wetting
  - See the big bulk, laminar flow, more indicative of what is seen probably in the loop itself
- Still analysis of results being done and new distributor to be tested next week to try for full wetting

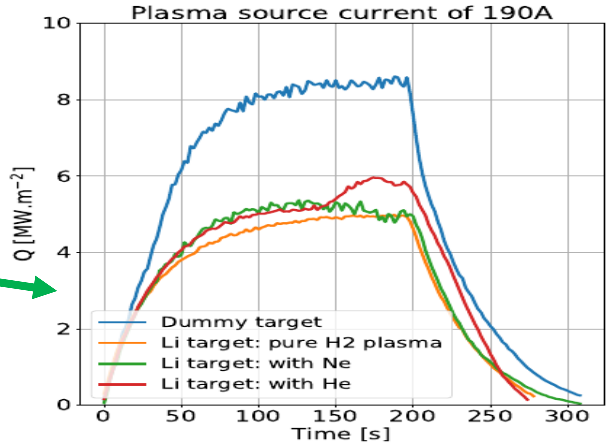


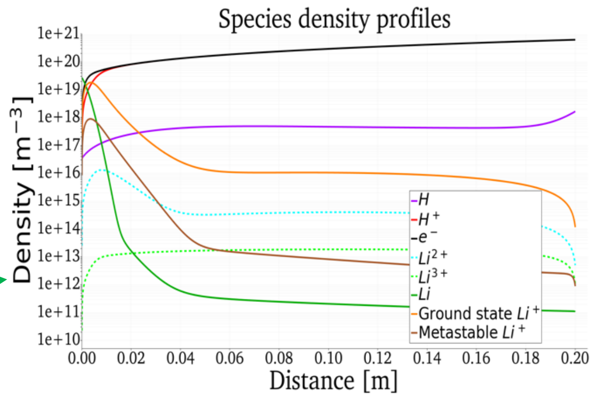




**D. Andruczyk, D. O'Dea, TOFE 2022**

# Collaborative Li vapor cloud experiments on MAGNUM-PSI and interpretive modeling conducted

- Experiments were carried out on Magnum-PSI at DIFFER to investigate Li vapor shielding in the presence of He and Ne species
  - Vapor shielding works in all cases
- New experiments to characterize the cloud structure were conducted in 9/2021
- Extension to a 1D model with coupling plasma chemistry code (CRANE) to a plasma transport solver (ZAPDOS) is underway

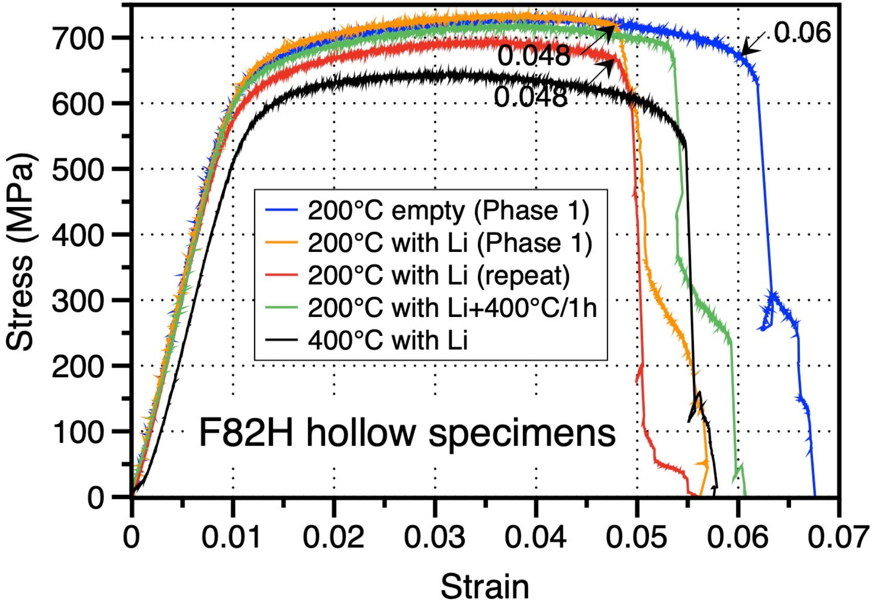



R. Rizkallah, SOFE 2021

# Experiments at ORNL look for signs of embrittlement between liquid Li and RAFM steel at elevated temps.

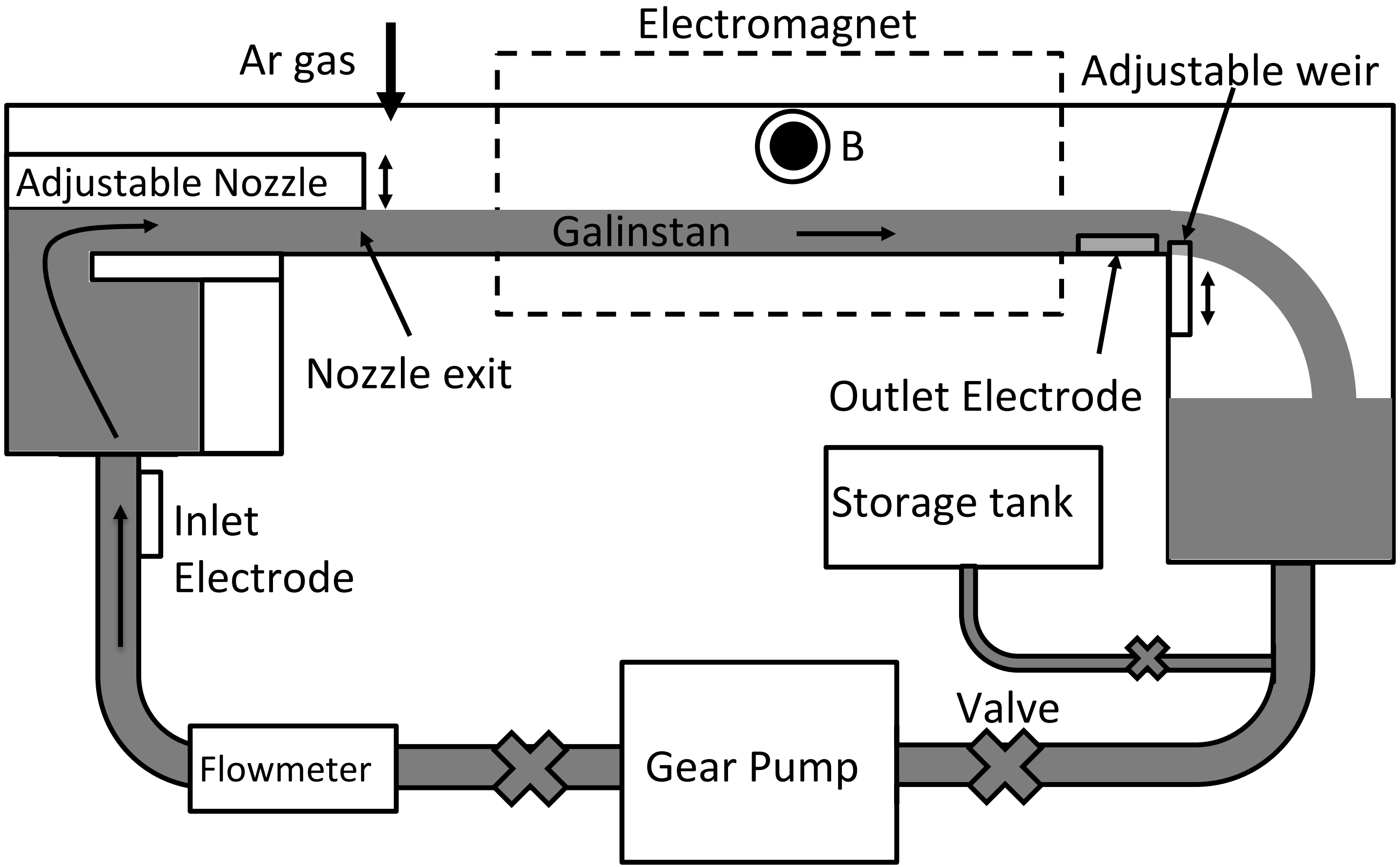
- **Embrittlement:** Liquid Li with RAFM (F82H)
- Two tensile specimens with Li inside and one with Ar inside
- Compatibility at 200 °C, as expected
- Additional tests in progress




B. Pint

# Prototypical liquid metal flow experiment: linear device with applied magnetic fields, extensive diagnostics

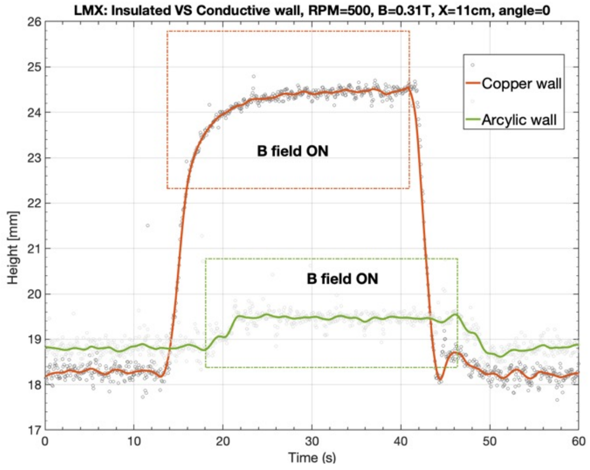


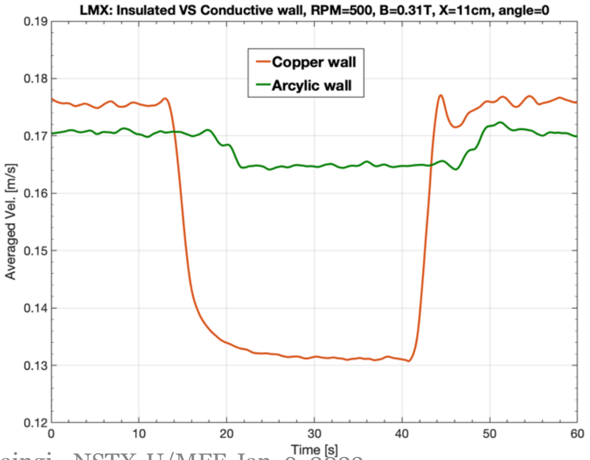


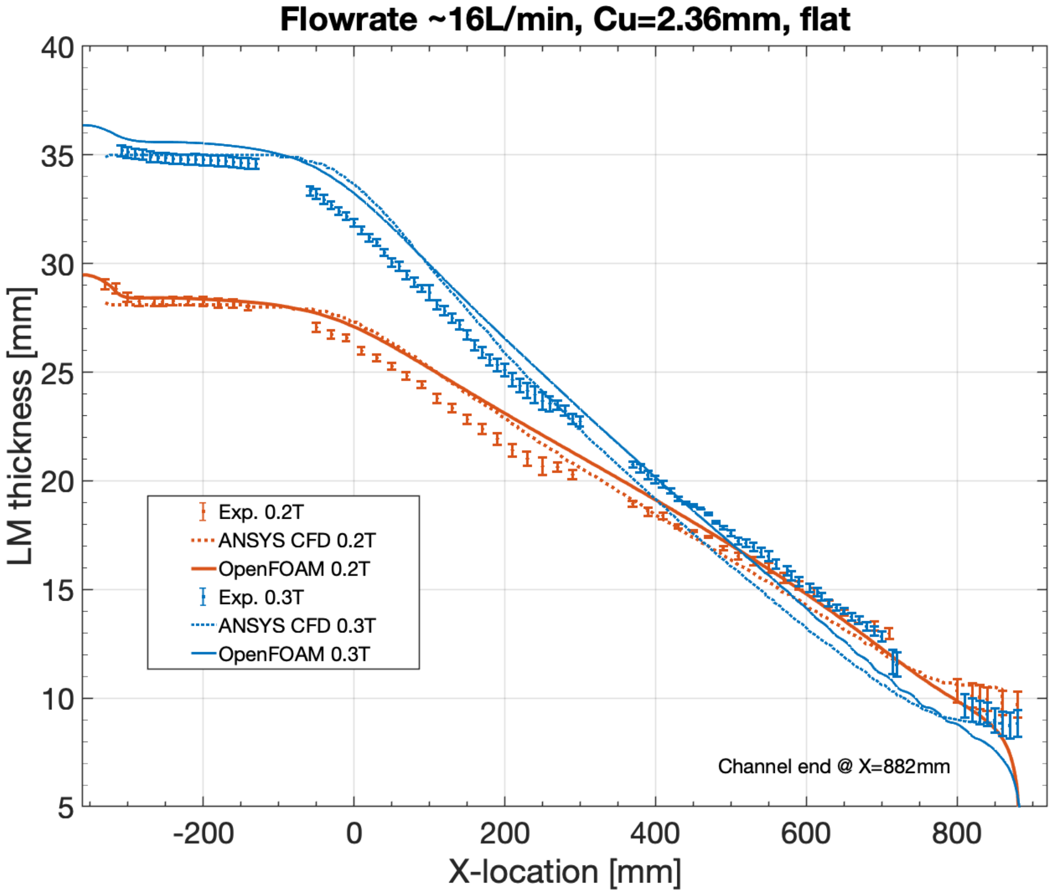

E. Kolemen

# Model validation experiments in LMX with insulated (reference) and conducting walls (copper insert)



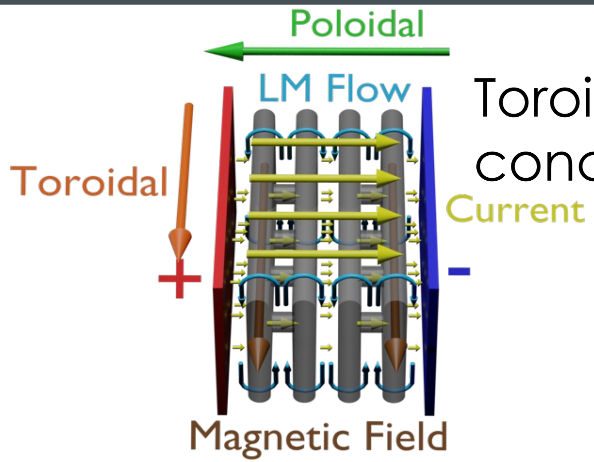


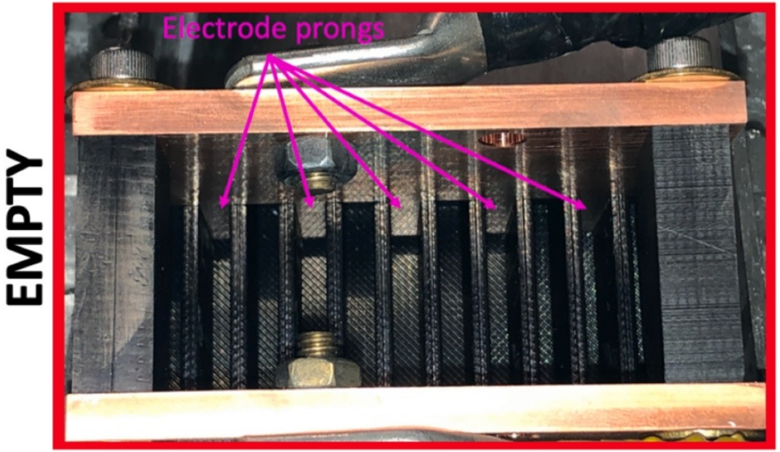



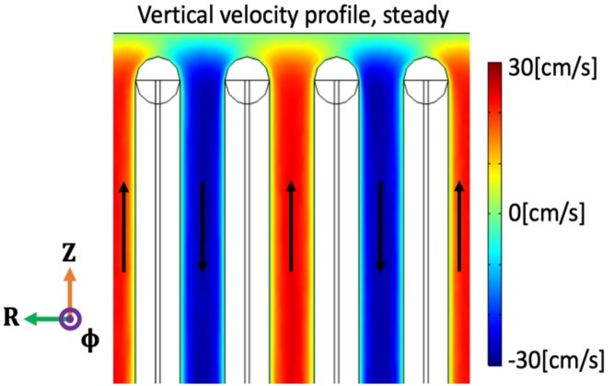

**Z. Sun, TOFE 2022**

# Divertorlets being developed: short flow path, modest flow to achieve desired heat exhaust




Toroidal divertorlet concept being tested





A. Fisher, E. Kolemen, NME 2020; F. Saenz, NF 2022

# Good progress made in domestic LM PFC design program



- A design window to operate liquid Li divertor PFCs with low evaporation (i.e. < 450 $^{o}$C) has been identified for a simplified 3-leg geometry
  - Self-consistent between LM MHD, heat transfer and plasma modeling
  - Required Li PFC flow speeds ~ 5-15 m/s
  - Two options: a LM jet with high initial speed, and j x B driven flow
  - Li retained in divertor: upstream Li concentrations $\leq$ 1% up to $10^{23}$ Li flux
- Single effect test stands studying wetting with an integrated Li loop
- Linear channel flow experiments are validating the same LM flow codes used for FNSF design
  - Good progress on novel divertorlets concept

# US LM PFC design program was renewed for 2023-2025



- Next step: evaluate liquid Li divertor PFCs with some evaporation (i.e. $\geq$ 500 $^{o}$C) as a function of flow speed
- Next step: evaluate impact of differences between published FPP-like designs and FNSF on Li PFC design requirements
- Next step: continue experimental work, including a new scoping of removing Tritium from liquid Li via electrolysis

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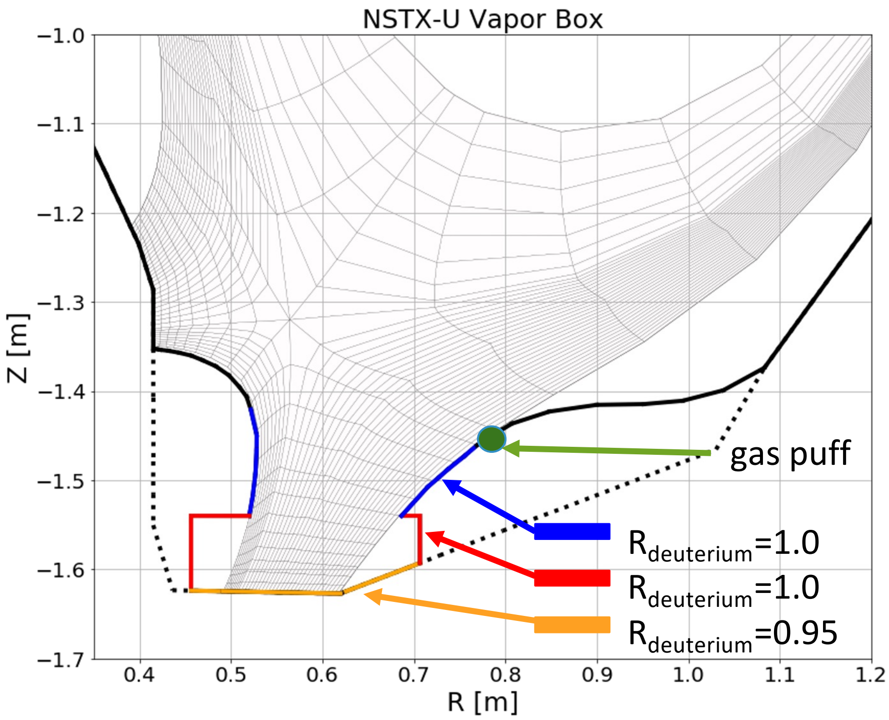
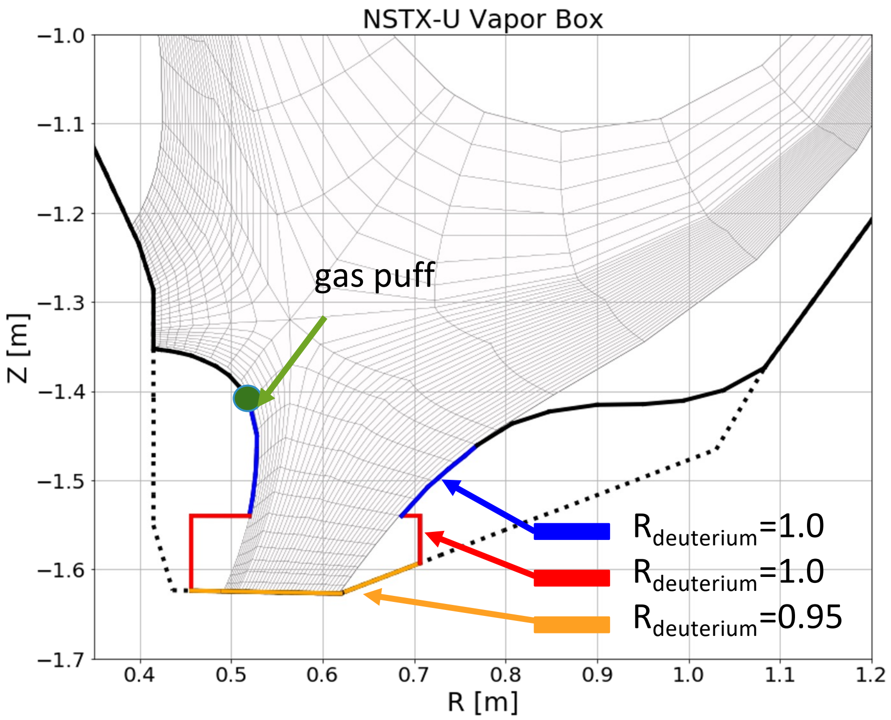
# Lithium Vapor Box compared with 'Slot' for NSTX-U

- $P_{heat}$ 1-10 MW, $q_{peak}^{div}$ unmitigated 65-92 MW/m$^2$

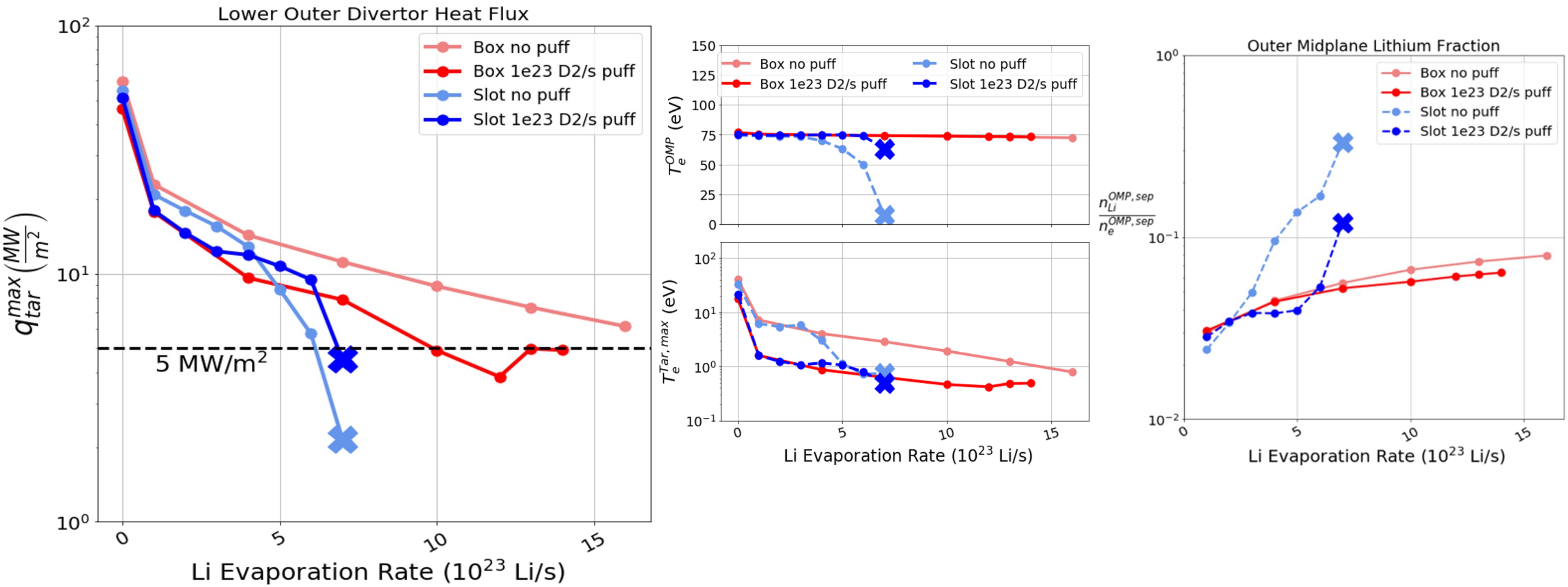



E. Emdee, Ph.D. 2022, ISLA 2022

# Private flux region D puffing more effective at retaining Li in divertor, while common flux region puffing reduces peak heat flux more



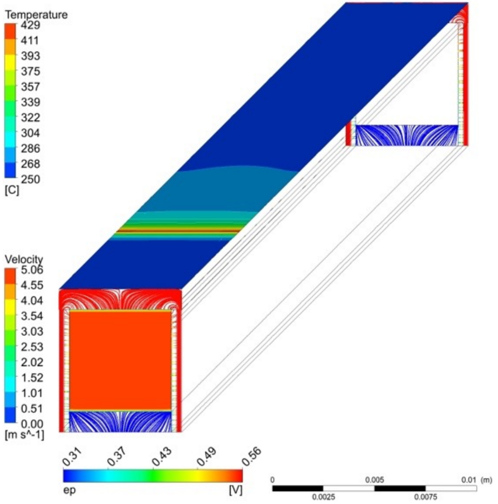


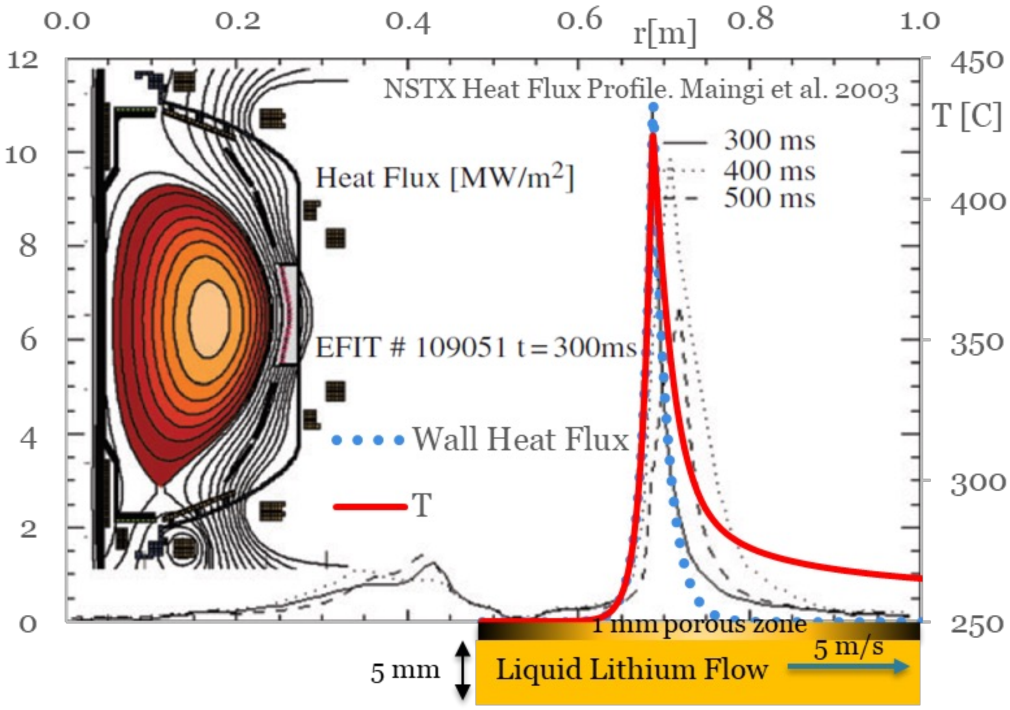



E. Emdee, Ph.D. 2022, ISLA 2022

# CPSF concept simulated with NSTX heat flux profile

- CFD analysis using CFX code
- Numerical Simulation of the flow in the lithium channel with porous first wall
- Exponential Heat Flux profile is imposed; $q_{peak}$ ~ 11 [MW/m$^2$]
- Surface temperatures below 450 °C can be achieved at 5 m/s Lithium velocity

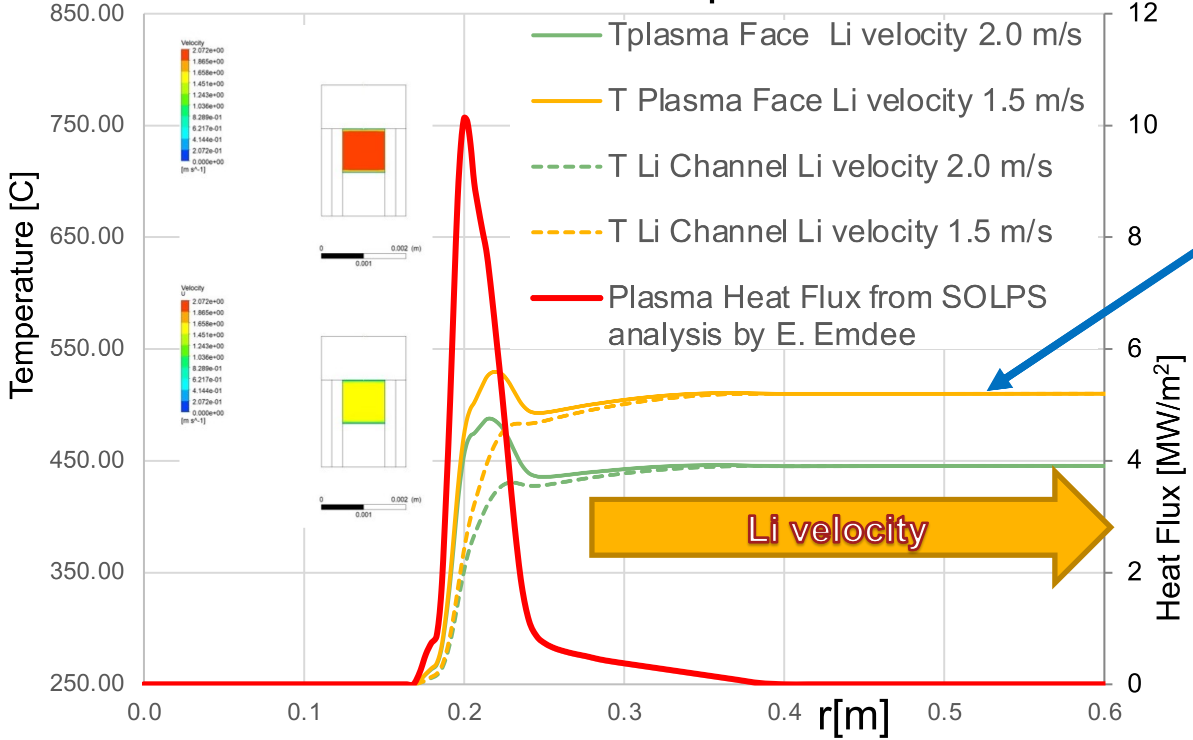



A. Khodak, ISLA 2022

# CPSF can be designed to create constant temperature evaporating surface suitable for Vapor Box Concept

CFD MHD Analysis of 1 mm square Lithium channel with 1mm porous wall



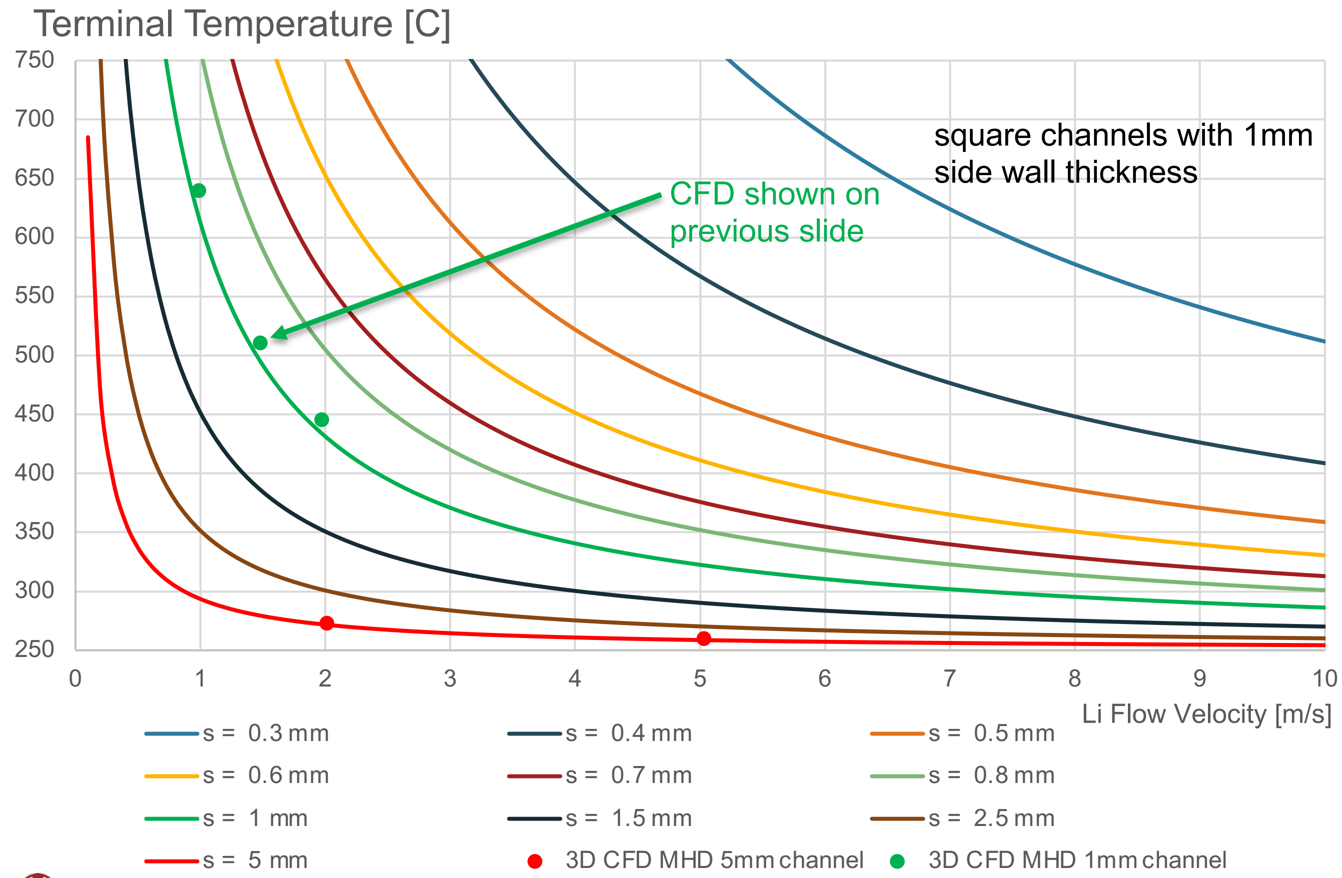

1mm square cross-section channel with 1mm porous wall provides constant temperature distribution on plasma surface ~500C at 1.5 m/s
This temperature level is targeted by Vapor Box divertor System

Temperature level is defined by:

1. Incoming Heat Flux
2. Lithium Velocity
3. Channel Size

A. Khodak, ISLA 2022

# Parametric studies define parameters of CPSF System




~500C temperature level is currently targeted by Vapor Box divertor System

Analytical Model Result are confirmed by CFD analysis

A. Khodak, ISLA 2022

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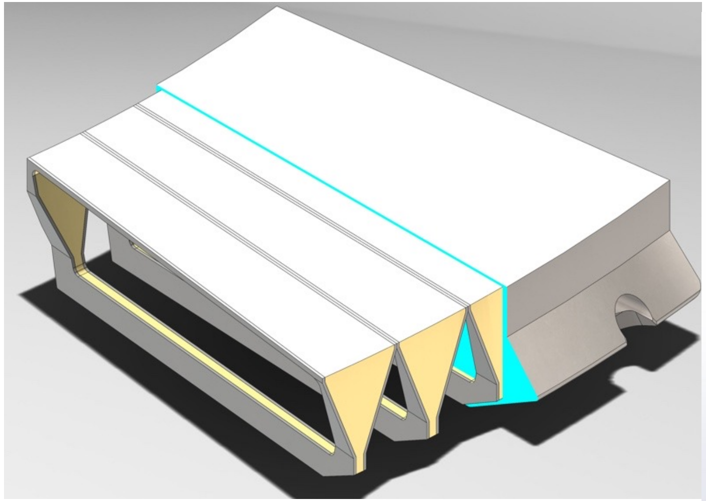
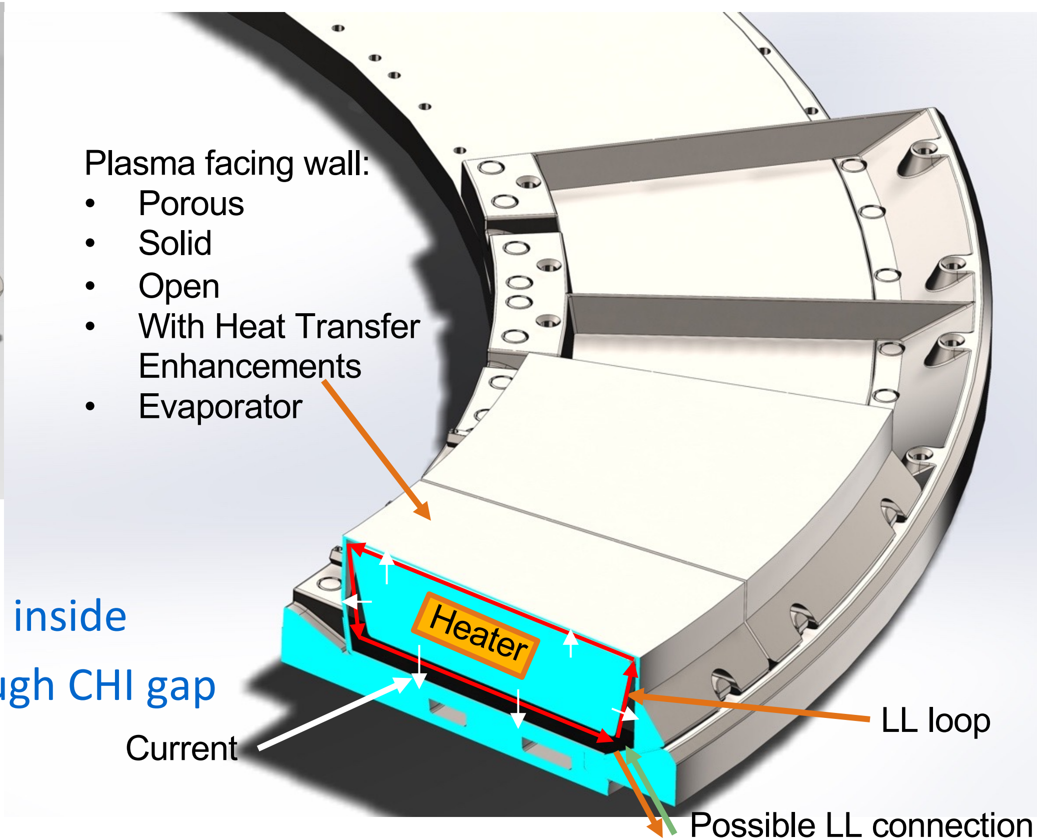
- Linear channel flow experiments are validating the same LM flow codes used for FNSF design
- Pre-conceptual design initiated for NSTX-U Li PFCs, based on FNSF design concepts

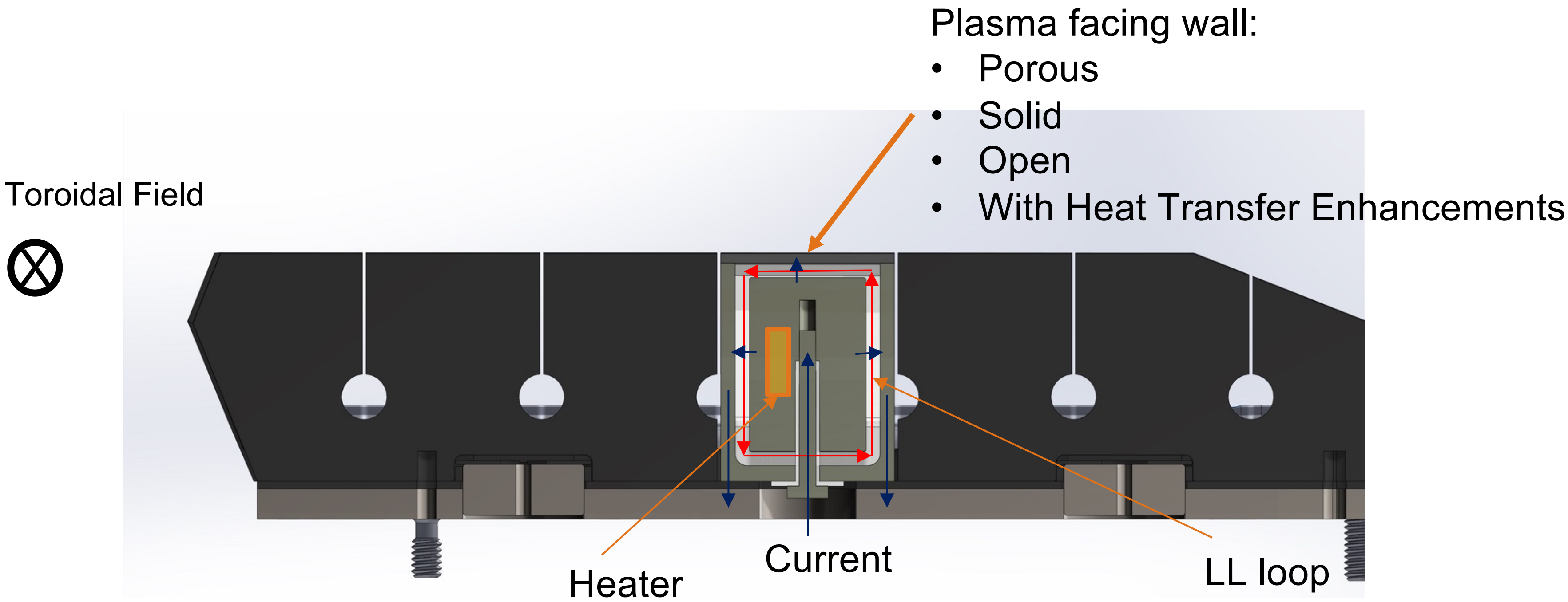
# Thank you for your attendance





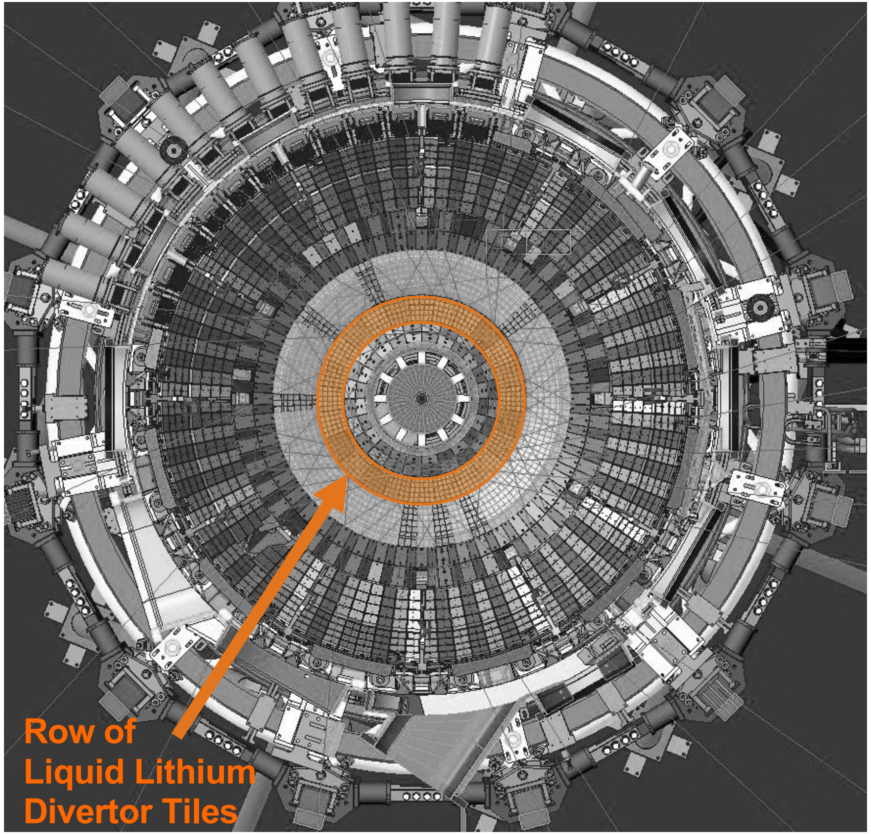

- Tile with 5 LL loops.
- Electric heater incorporated inside
- Possibility of LL supply through CHI gap

# Minimalistic concept: tile with insert




- Tile with cutout and close LL loop insert.
- Electric heater can be incorporated inside the insert

# Proposed Row of NSTX-U Divertor Tiles with Liquid Lithium




Khodak