National Spherical Torus eXperiment Upgrade

Liquid metal PFC program for NSTX-U

NSTX-U PAC40 – Sept. 11, 2019

Rajesh Maingi

(Partial response to Charge #3 and comments in the last PAC report)

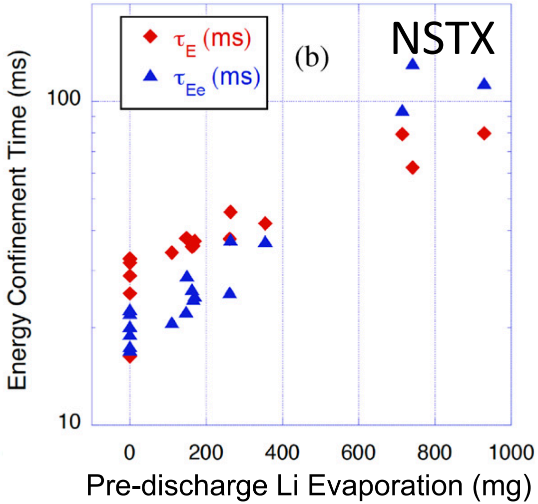
Substantial excitement and opportunities with an accelerated liquid metal PFC program in NSTX-U

- Liquid metal PFCs are a PPPL strategic initiative
  - PPPL effort engages multiple departments: PS&T, I&T, NSTX-U
- *This talk motivates near-term deployment concepts, but the elements are presently unfunded*

- Motivation and recent developments
  - New FES domestic liquid metal PFC development program: FY20-FY22
- Near term acceleration options and next step vision
  - 'Phase 1' options: pre-filled Li plugs in high-Z tiles, flowing Li limiters
  - 'Phase 2' vision: all high-Z tiles with flowing Li divertor modules
- Summary

Liquid metal plasma-facing components should be vigorously pursued as an alternative to solid PFCs

- High-Z solids are the leading PFC design choice, but have serious challenges for long-pulse reactors
  - Performance under intense PMI and neutron load
- Liquid metal PFCs offer the promise of self-healing PFCs that do not suffer from lifetime erosion & re-constitution limits
  - Remove surface heat load requirements on solid PFCs
  - Remove requirement that solid PFCs handle simultaneously PMI and neutrons
  - Aim to remove microscopic PMI-generated debris in LM flow
  - Li PFCs provide access to high τ_E, one path to a compact fusion pilot plant



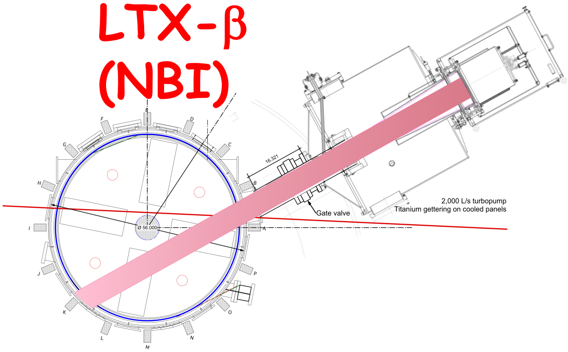
R. Maingi, *Nucl. Fusion* **52** (2012) 083001

Developments since PAC-39 (1/18)

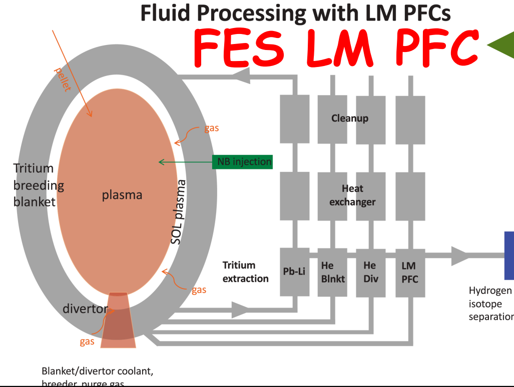
- DoE/SC Phase 2 Assessment of NSTX-U Recovery Plans strongly endorsed the liquid metal PFC program for NSTX-U (3/18)
- Transformative potential of LM PFCs identified in reports (2018 FESAC TEC, 2019 NAS Fusion Strategy)
- DoE LM Fusion Energy Systems Study (FESS- 2/19) identified general R&D needs and those specific to liquid metals of interest: Li, Sn, Sn-Li
    - **Follow-on FES LM PFC design program launched (FY20-22, PPPL lead)**
- PPPL interest centers on using flowing liquid Li, but leaving flow speed as a design choice
    - **Slow flow (cm/sec): capillary porous system or vapor box**
    - **Fast flow (m/sec): LM flow augmented by j x B drive**

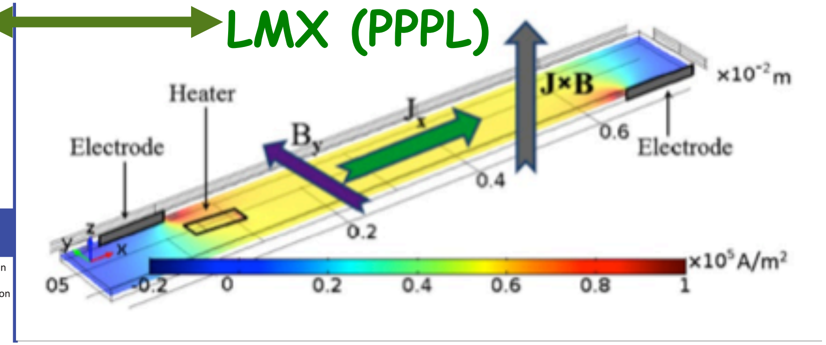
Elements of PPPL liquid metal PFC program

LTX-β (NBI)

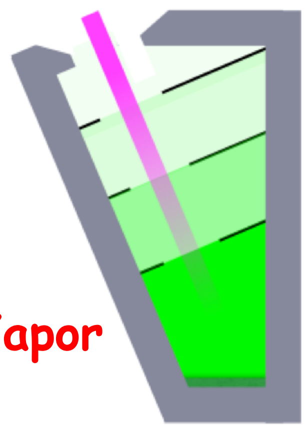


FES LM PFC ⟷ LMX (PPPL)

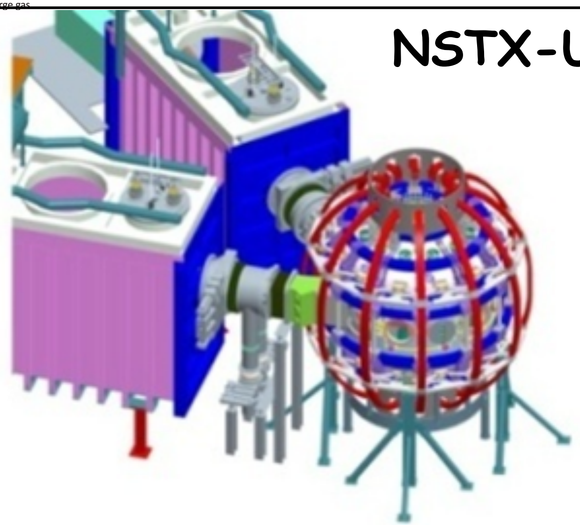


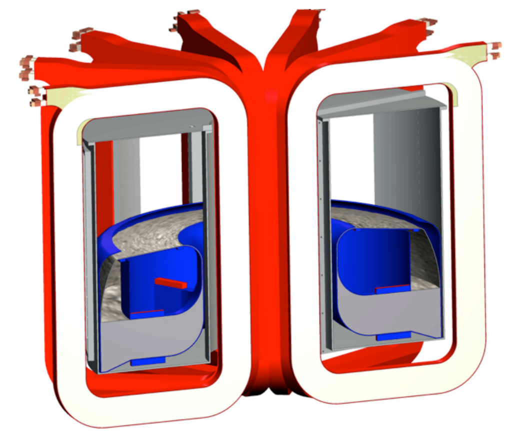


Li Vapor Box (MAGNUM)



NSTX-U





FLIT design - unfunded

A LM PFC Development Program has been initiated, following the FESS LM PFC study

- **What**: three-year program ($1M/year) toward engineering concept design for LM PFCs for reactors [PPPL, ORNL, UIUC, UCLA]
- **Why**: because it is uncertain that solid PFCs can survive plasma-material interactions at reactor scale, and LMs may provide a solution
- **Goal**: <u>Develop and evaluate a LM PFC concept for an FNSF / compact fusion pilot plant</u> (CFPP) core plasma via
    1. Engineering design and plasma interface calculations
    2. Appropriate lab experiments (single-effect and prototypical flowing LM) to simulate the concept and answer questions
- **NSTX-U Relevance:** new designs applicable to a CFPP could be scaled and tested in NSTX-U if resources become available
    - Path to close gaps for CFPP plasma exhaust design

Down selections for the initial LM PFC program

- Engineering concept design for a flowing liquid lithium PFC for the divertor only
  - Flowing liquid walls are a future consideration

- First option: low temperature below the strongly evaporative limit (expand to higher temp. in years 2-3)

- Evaluate several flow rates: slow, medium and fast

Science and Engineering Open Questions

- What are the trade-offs for slow-flow (< 10 cm/s) and fast-flow (> 1 m/s) concepts? Is there an optimum intermediate flow rate? What are safety implication of each? How are they integrated into the plant?

- How can we insure maximum wetting on the substrate? How can we avoid dryout? How can we minimize droplets?

- What reactor-relevant design features can be simulated by an open-channel chute experiment?

- Can we remove hydrogen from the flowing Li sufficiently fast? Can we pump He?

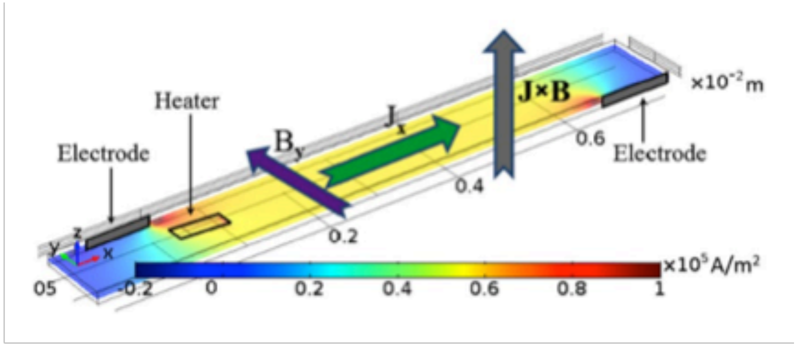
Plan, FY 20

- Concept Development: Engineering Concept Design & Plasma Interface for **flowing liquid Li divertor** PFCs for future devices (FNSF/CFPP) – **675k** [ORNL, PPPL, UCLA, UIUC]
  - Three flow rates: slow, medium, fast – open questions as a function of flow rate?
  - PFC surface temperatures for low evaporative solutions: T < 400-450^{o} C
  - ➢ **2D SOL/divertor and PMI near surface modeling a critical part**
- Lab Experiments: Single effect and Prototypical Experiments – **325k**
  - **Experiments on wetting, continuous flow, dryout, texturing [UIUC]**
  - **LMX experiments to determine range of flow rates and dependence on B, thickness, heating [PPPL]**
  - **Liquid Metal Embrittlement [ORNL]**
- 3 year goal: **develop design and identify design trade-offs for FNSF/CPP** consistent with LM MHD, substrate thermo-mechanics and CFD, plasma interface, and accessible experimental validations

Liquid Metal Experiment: LM Flow Experiment at PPPL

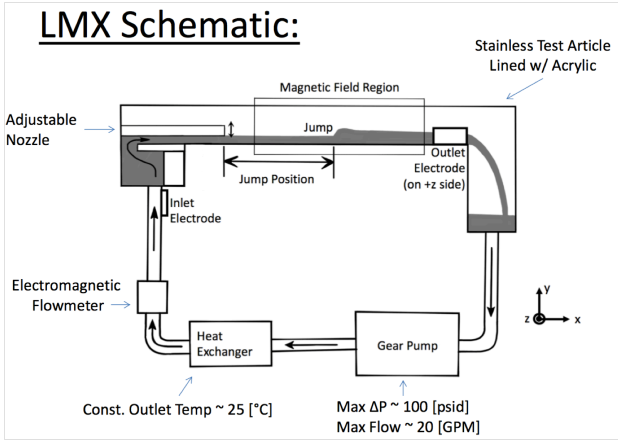
LMX is a chute flowing experiment, using GaInSn (safe, can be open to air or water)

- B_{max} = 0.33 T, uniform, perpendicular to flow
- Chute width, length = 10.9 cm, 70 cm
- LM thickness ~ 2 cm, v ~ 1-3 m/s
- Electrodes for driving currents
- Piping, chute, other parts are plastic
- Low temperature (25 C)



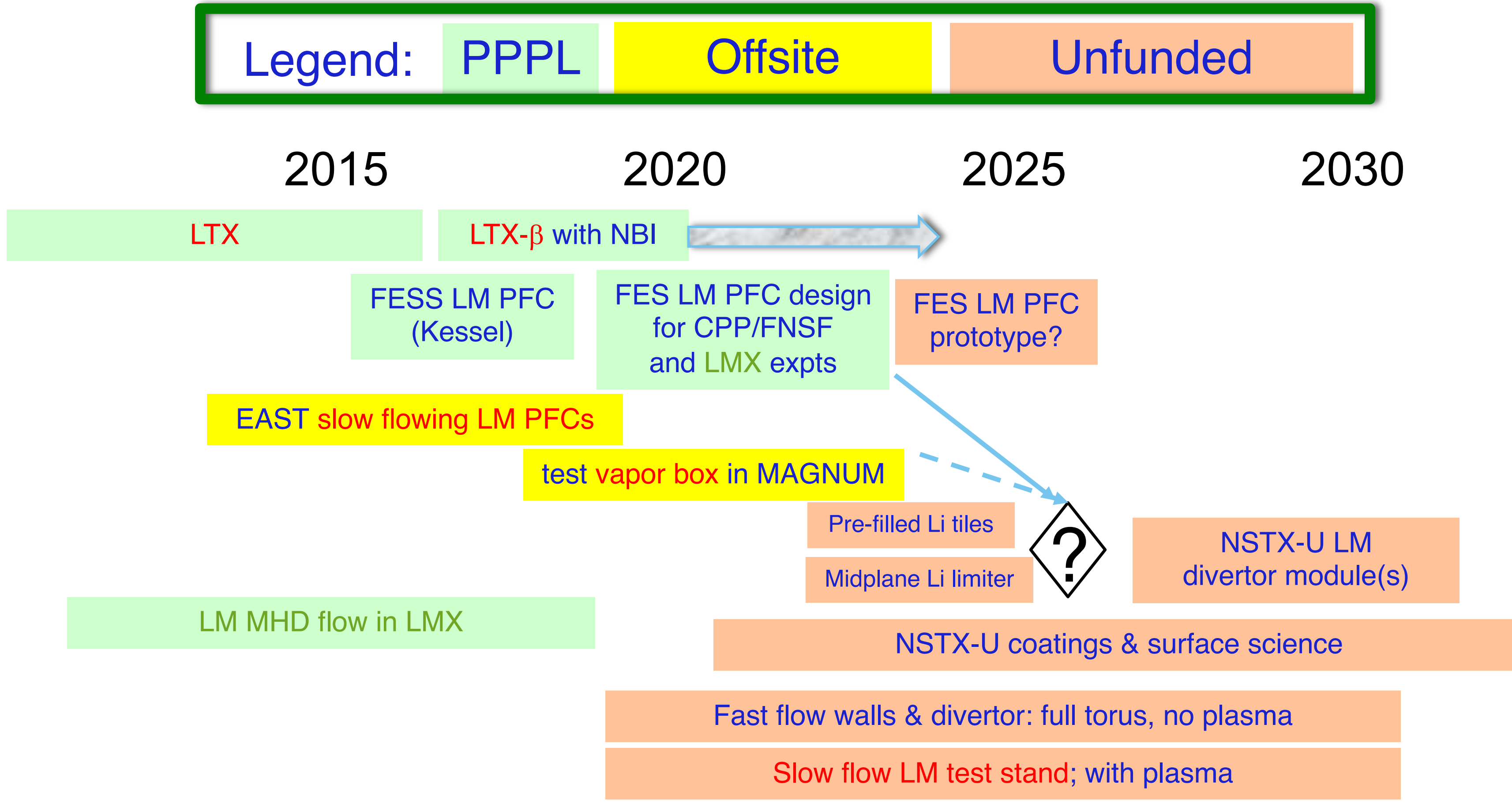
Year 1 experiments

- **LM MHD flow vs simulations**
- **Heating/mixing vs simulations**
- **Nozzle size/flow speed vs simulations**
- *Detailed examination of upgrades/parameter space accessible/what is prototypical of concept design*



M. Hvasta et al., *Nucl. Fusion* **58** (2018) 016022
M. Modestov et al., *Nucl. Fusion* **58** (2018) 016009

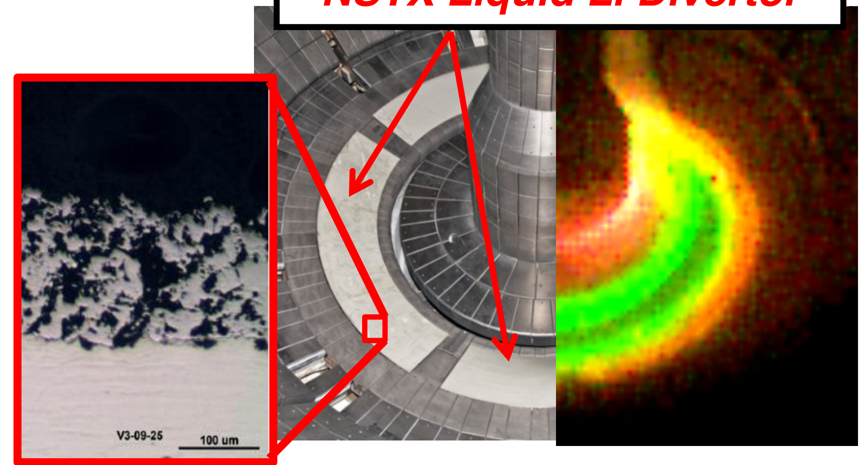
Elements of PPPL liquid metal PFC program

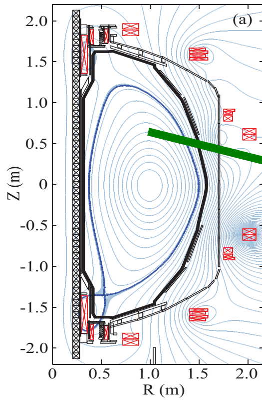


The need for integrated solutions, coupled with NSTX & PPPL expertise, motivates liquid metal PFC mission in NSTX-U

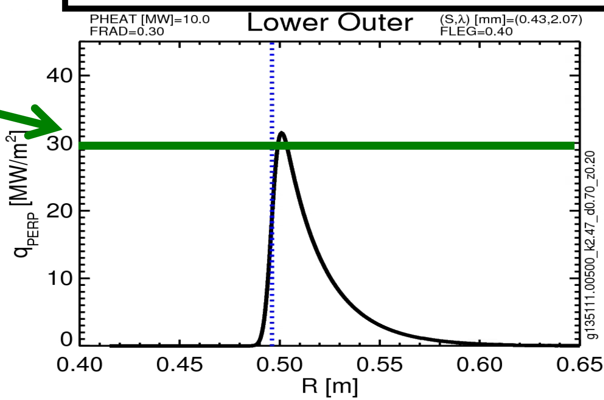
- Li science and technology developed in NSTX & PPPL
  - NSTX LLD: Diagnostics, Theory, and Surface Science
  - CDX-U, LTX, LTX-β, collaborations
- NSTX-U can access $q_\perp \leq 30$ MW/m^2
  - Full heating power: P/R~20

NSTX Liquid Li Divertor





NSTX-U projections

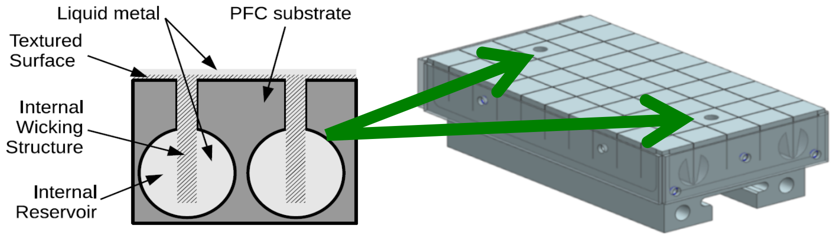


Outline

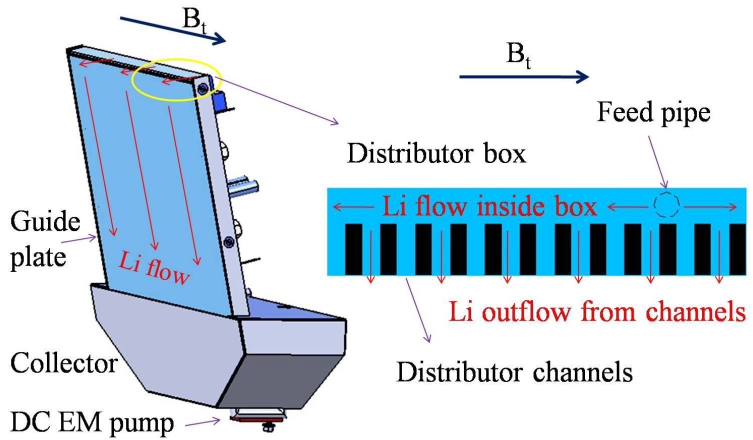
- Motivation and Goals
- **Near term acceleration options and long term vision**
  - Phase 1 Option: pre-filled lithium plugs in high-z tiles
  - Phase 1 Option: upgraded flowing liquid lithium limiters
  - Phase 2 Vision: all high-Z tiles with flowing Li divertor modules
- Summary

Two Phase 1 liquid Li options for deployment in NSTX-U in 2024

- Introduce Li atoms into divertor for particle and power exhaust
  - Pre-filled lithium plugs embedded in a high-Z substrate
  - Previously reviewed step (CDR) on path toward liquid metals in NSTX



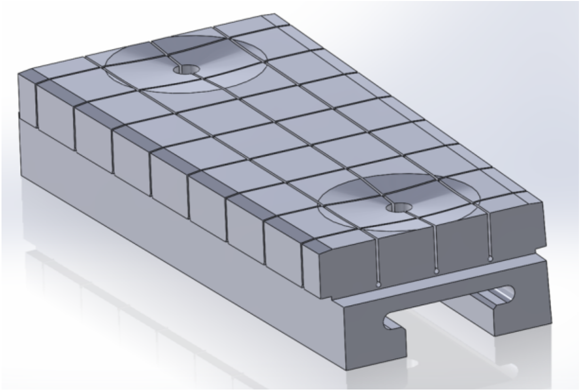
- Use flowing liquid lithium system for power and particle exhaust
  - First step: limiter inserted in midplane
  - Knowledge from three versions tested in EAST enables fast NSTX-U deployment

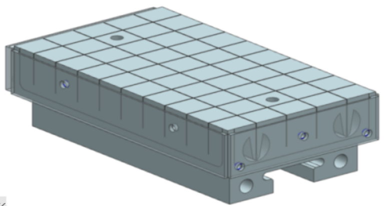


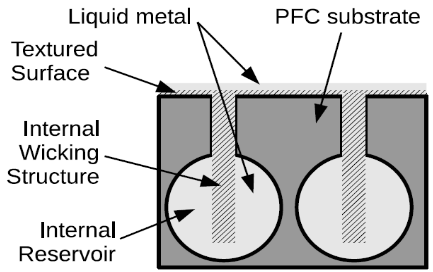
Pre-filled Li plugs in high-Z tiles were a previously reviewed step toward liquid metal PFCs

- Pre-filled targets build on high-Z, high-heat flux designs
- Use pre-heating to bring tiles to 200-300 ^{o}C, and strike point incidence to increase temperature for high evaporation rates
  - How to avoid surface contamination?
- Detachment physics: can Li evaporated into SOL and/or private flux region dissipate power?
  - Connect to simple Li vapor box concept
- Slow progress since 1/18 due to staff loss of critical expertise (M. Jaworski)

2015-16 NSTX-U High-Z Design

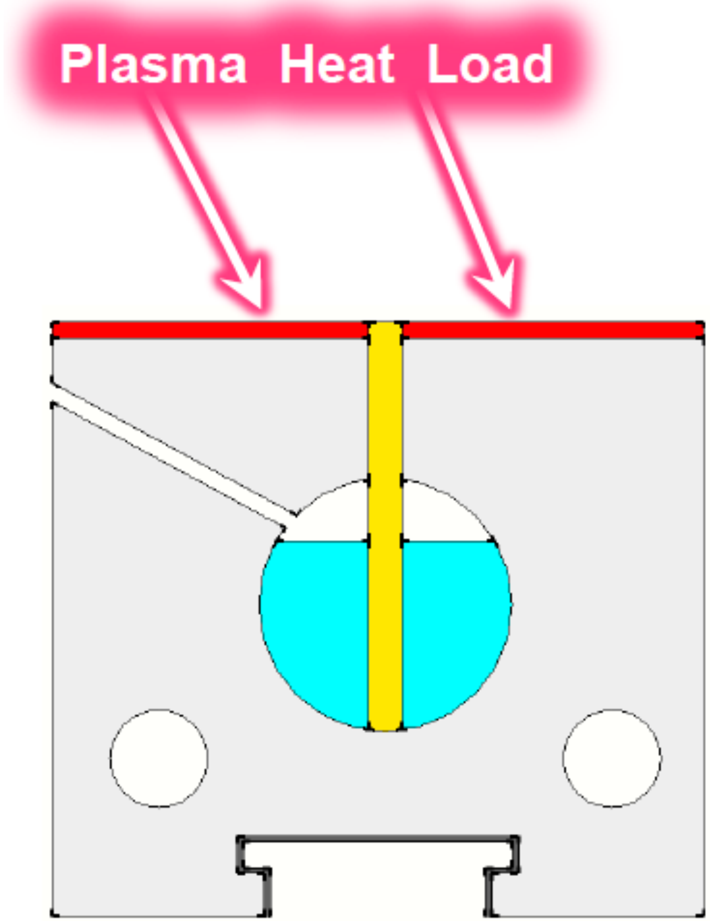






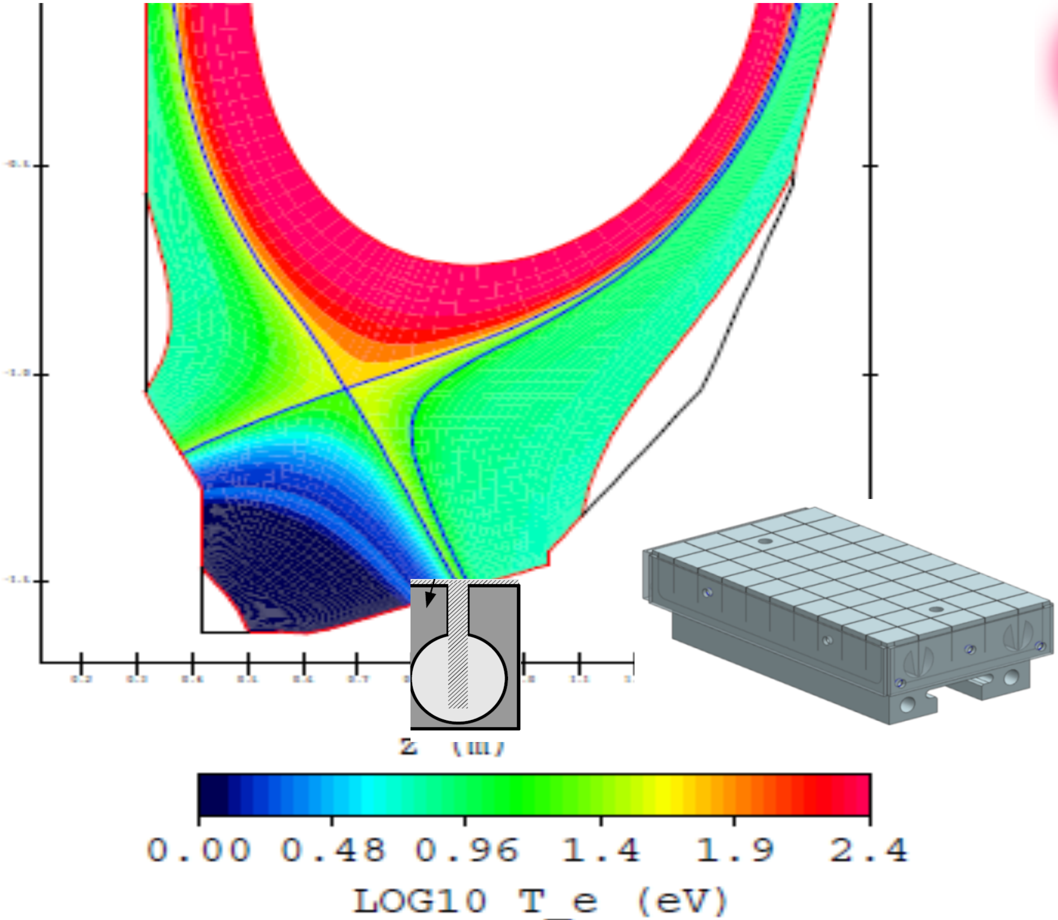
Pre-filled Li plugs in high-Z tiles aim to provide Li atoms into the divertor in NSTX-U

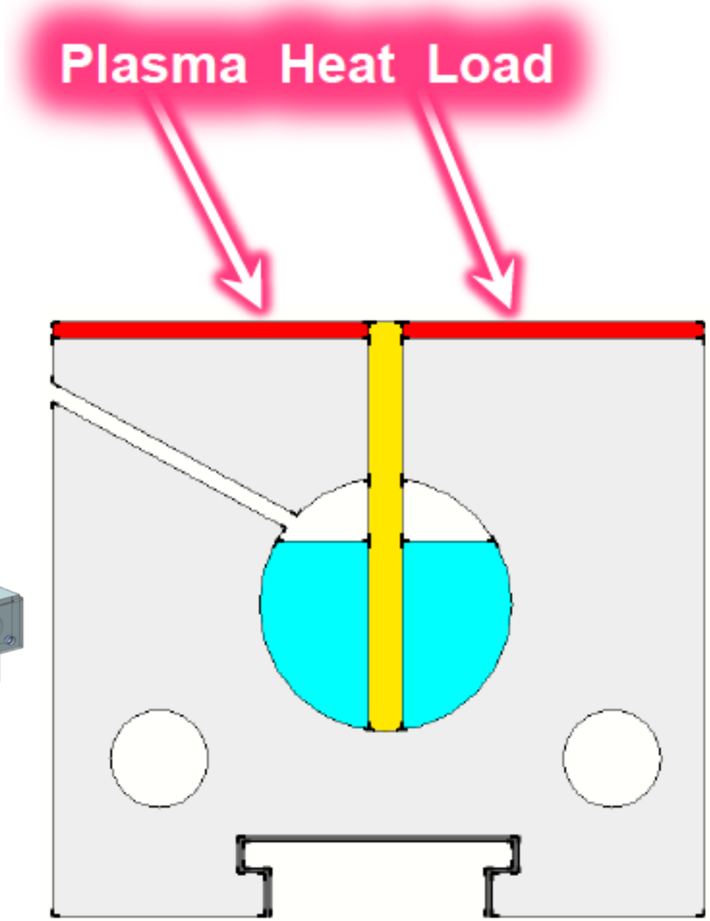
- Detachment physics: can Li evaporated into SOL and/or private flux region dissipate power?
  - Low temperature: pumping?
  - High temperature: power dissipation and detachment control?
  - Informing Li vapor box designs for NSTX-U in Phase 2
  - Can HeGDC clean surface contamination?
- Use strike point incidence to control local temperature
  - Capillary forces cause Li to wick up



P. Rindt, ISLA 2017, FED 2016

Pre-filled Li plugs in high-Z tiles aim to introduce Li atoms into the divertor

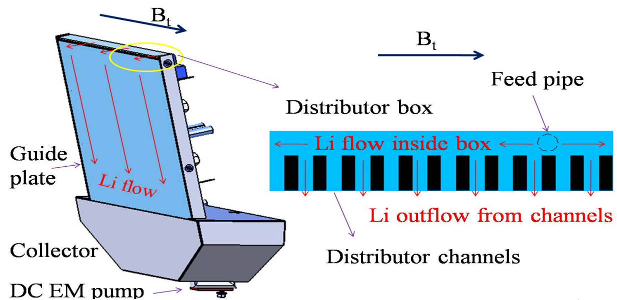


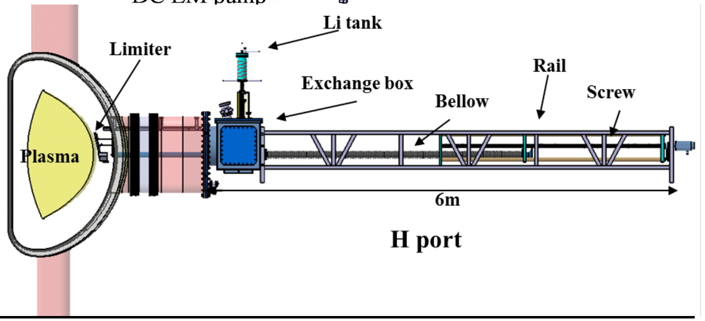


P. Rindt, ISLA 2017, FED 2016

The science and technology of flowing liquid lithium limiters has been advanced via US-PRC PMI collaboration on EAST

- Three generations of midplane liquid lithium limiters tested in EAST
  - Prototype SS plate tested in HT-7
  - Gen. 1 (12/2014) tested in EAST
  - Gen. 2 (12/2016) tested in EAST
  - **Gen. 3 (8/2018) tested at UI-UC and PPPL and then EAST**
    - **Increasing P_{aux}, W_{MHD}**



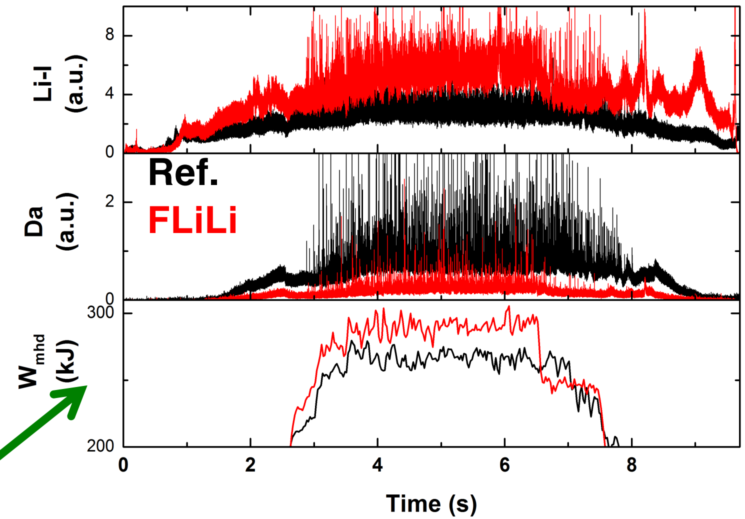


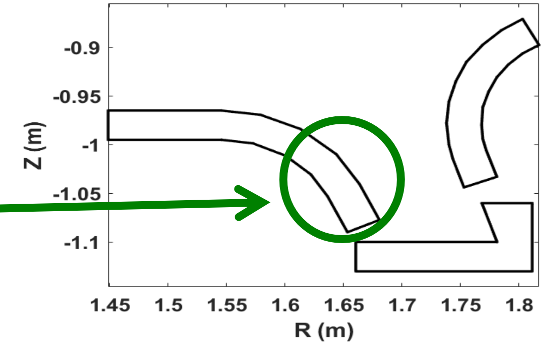
Generation	Heat Sink	SS thickness (mm)	JxB pumps	Max. P_{aux} (MW)	Max. q_{exh} (MW/m^2)	Max. W_{MHD} (kJ)
1	Cu + SS	0.1	1	1.9	3.5	120
2	Cu + SS	0.5	2	4.5	4	170
3	Mo (TZM)	NA	2	8.3	TBD	280

J. Ren, Rev. Sci. Instrum. **86** (2015) 023504
G.Z. Zuo, Nucl. Fusion **57** (2017) 046017
J.S. Hu, Nucl. Fusion **56** (2016) 046011
R. Maingi, IAEA FEC 2018 paper FIP/3-5Ra

EAST: 3rd generation flowing liquid Li limiter fabricated; shipped to EAST 6/18 and exposed to plasma 8/18

- Made of Mo for Li compatibility
  - One plate sent to EAST, second plate sent to UI-UC for testing in HIDRA
  - Extensive heater testing at UI-UC
  - Stainless steel distributor and collector brazed onto plate
- Experiment in 8/18 exposed FLiLi limiter to plasmas with P_{aux}=8.3 MW @ 3cm from separatrix
  - Reduced recycling, slightly higher stored energy, low or no sputtering, ELM mitigation
  - Future versions: 3D printed W PFC, limiter and/or divertor sector(s)?





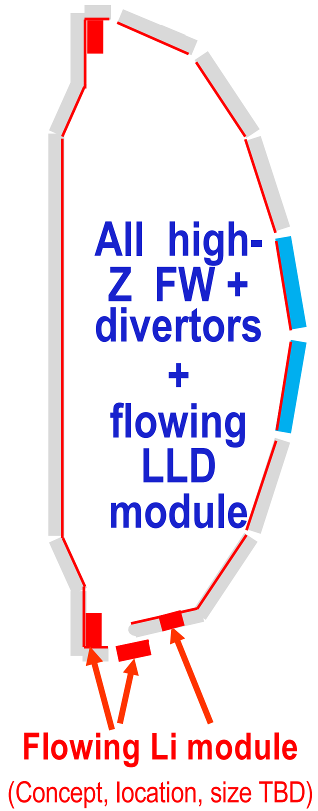
R. Maingi, IAEA FEC 2018 paper FIP/3-5Ra

Flowing liquid Li midplane limiters, based on FLiLi technology developed collaboratively on EAST, can be designed for NSTX-U

- Potential upgrades – technology that enables science
  - Increase flow rate from cm/s to m/s with e.g. j x B forces or LM jets to increase convective heat removal
  - Increase range of temperatures up to strong evaporation limits (650 ^{o}C) to augment power dissipation and detachment
  - Increase range of Li film thickness from 0.1mm to 1 cm for improved protection of substrate
- Can we restart flow after stopping?
- Can we improve wetting and reduce creep with texturing?
- Can we extend these concepts to a flowing divertor system?

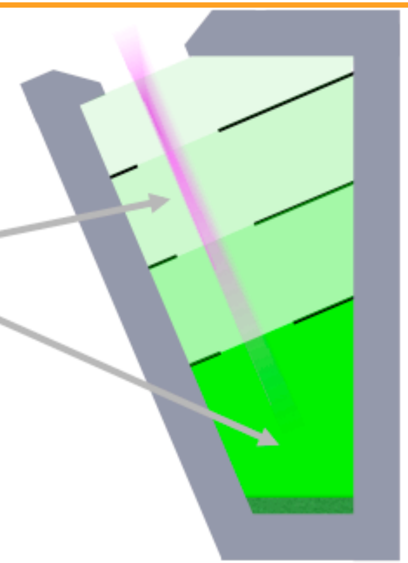
Phase 2: Long term vision and directions of LM program in NSTX-U

- NSTX-U would transition to all high-Z PFCS
  - Avoid carbon, due to formation of compounds that contaminate Li (LTX, NSTX LLD experience)
  - Aiming for very high τ_E, flat temperature profiles as observed in LTX
  - Coming LTX-β results will highlight importance of liquid vs solid walls
- High heat flux regions would have flowing liquid lithium module(s) for power exhaust
  - Multiple concepts can be tested over the years
- Low heat flux regions would have pre-filled tiles or evaporated coatings for particle control
  - Cryopump could be installed as a future option for a detailed comparison with Li pumping
- The new FES LM PFC Development Program should lead to natural collaborations during design and deployment



Li vapor box (LVB) divertor concept

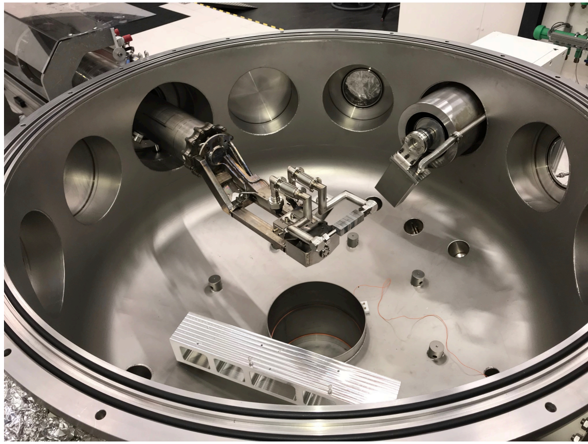
- **Provide a localized cloud of Li vapor <u>away from main plasma</u>**
  - **Evaporation at ~ 700° C**
  - **Condensation at ~ 400° C (determines DT pumping or not)**
- **Returns liquid lithium via capillary porous material ~ 1 kg/s (Fast flow systems require ~ 1 t/s)**
- **An inside-out heat pipe – with the heat source inside the pipe!**
- **Vapor gradient ⇒ resilience to variable heat flux**
- **Cannot be done with gaseous impurities**



R. Goldston, *Phys. Scr.* **T167** (2016) 014017
R. Goldston, *Nucl. Mater. Energy* **12** (2017) 118
E. Emdee, *Nucl. Mater. Energy* **19** (2019) 244

LVB Proof-of-Principle Experiment at MAGNUM-PSI (LDRD)

- **Demonstrate volumetric dissipation in lithium vapor**
  - **Target heat flux should drop by large factor**
  - **Power should be distributed ~ evenly around box**
- **Demonstrate robustness to varying plasma power**
  - **Beam should move into densest box by a factor of ~ 2 for 2x higher power**
  - **Is it lithium pressure or lithium influx that counts?**
- **Answer key scientific questions:**
  - **How is power dissipated?**
  - **How is momentum dissipated?**
  - **Requires substantial diagnosis**
- **New LDRD supports postdoc to participate in LVB design and experiments**



Target Staging Area

Liquid lithium experiments on NSTX-U can begin as early as 2024

- Phase 1 requires immediate design effort
  - Would need FES agreement to deploy a few NSTX-U Recovery engineers and designers (in 2020) for these upgrades

- Preparation for phase 2 vision by 2026-2027 needs to commence
  - NSTX-U engineers and designers also needed for qualifying high-Z tile designs on divertor and wall
  - The FES LM PFC development program will naturally provide CFPP relevant designs, which require engineering and scaling to NSTX-U, as well providing a pool of engaged collaborators

Backup

US PMI workshop 2015 and FESAC TEC 2018 reports highlighted the importance of developing LM PFCs

- PMI Workshop: Multiple priority research directions (PRDs) highlight need to advance concepts (including **liquids**):
  - PRD-A: limits on power and particle handling, including **liquids**
  - PRD-B: demonstrate dissipative divertor solutions, including **liquids**
  - PRD-C: develop solutions for main chamber components and tools for sustained operation
  - PRD-D: science of evolving materials, including **liquids**
  - PRD-E: understand impact of **materials** on core performance

- FESAC TEC: identified both slow flow and fast flow LM systems as transformative enabling capabilities (TEC)
  - Slow flow and hybrid solid-liquid systems described in advanced material and manufacturing chapter
  - Fast flow LM systems described in a stand-alone chapter

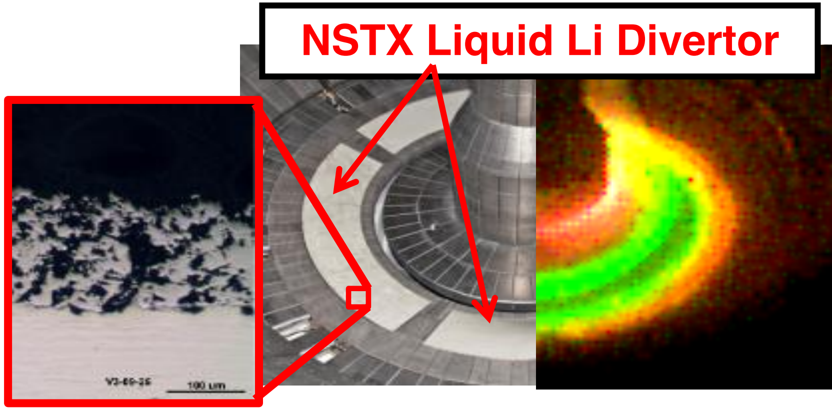
Goal: deploy flowing LM PFCs in a high power plasma device that are applicable to compact fusion pilot plants

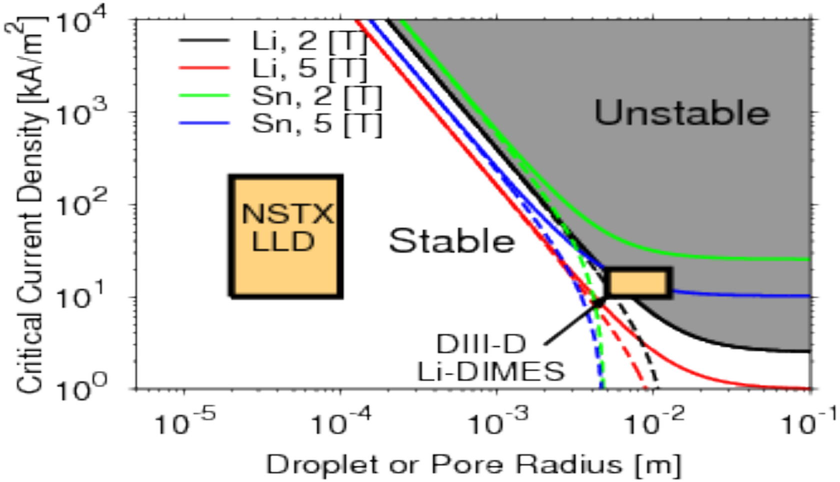
- Design options for flowing LM PFC:
  - What LM should be used? ***Near-term focus on Li****, but interest in Sn-Li and Sn*
  - LM PFC designs can provide particle exhaust, power exhaust, or both
    - Particle exhaust requires Li $\leq$ 300-400 ^{o}C; a fast-flow system (m/s) or a slow-flow system (cm/s), restricted to low heat flux regions, can do this
    - Power exhaust: either a fast-flow system, or a slow-flow system *at high operating temperature and vapor pressure* can do this
    - Both power and particle exhaust: a fast-flow system can do this; a high temp. slow-flow system may get pumping from low heat flux regions
  - ➢ PPPL program has parallel efforts on slow- and fast-flow Li systems

*** *Fast-flow systems augment the normal conductive power exhaust with convection, but fast-flow systems have more technical challenges (MHD drag, stable flow)*

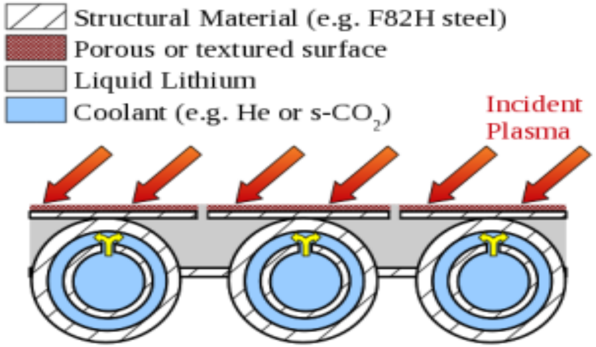
PPPL developing science and technology of liquid-metal targets for fusion devices: reactor-relevant concepts

- NSTX demonstrated stable liquid lithium divertor target
  - Stability predicted for structured substrates
- Heat-flux and cooling results in novel configurations: *continuous vapor shielding of targets*
- Impact: candidate reactor concept (T-("T-tube") shown below





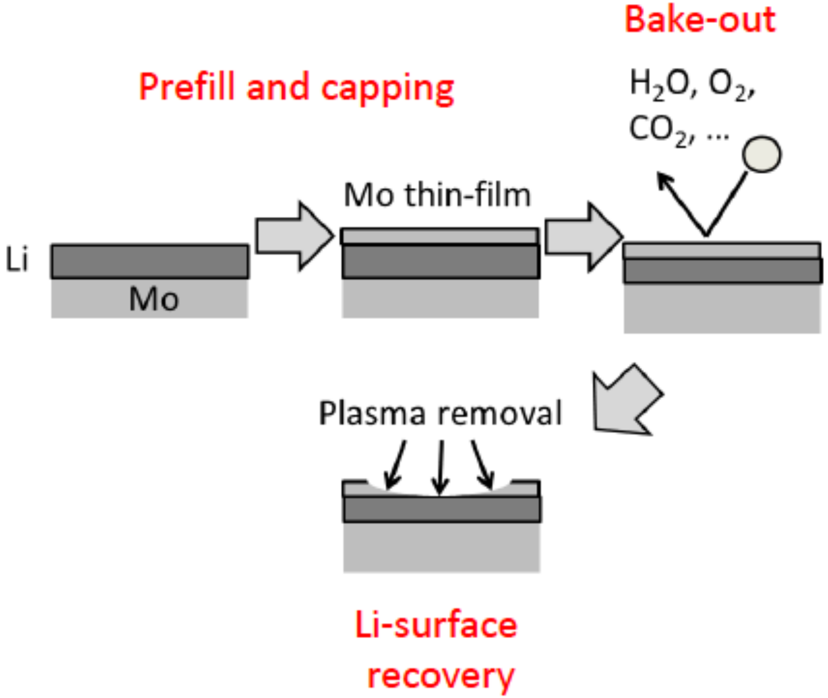
M. Jaworski, *Nucl. Fusion* **53** (2013) 083032

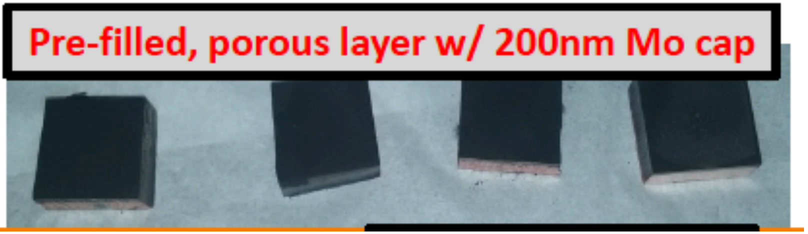


M.A. Jaworski, *PPCF* **55** (2013) 124040

Mo caps on pre-filled Li plugs would enable survival during bakeout

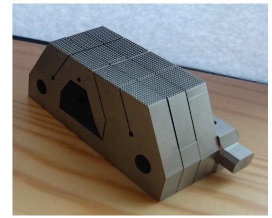
- Removable, macroscopic, metal covers and foils previously used but requires extraction strategy
- Thin metal foil can be removed in-situ by plasma bombardment
  - May require bias-able targets to enhance sputter yield
  - E.g. 1e17 m^{-3}, 200V bias He->Mo: 1000s (~15min) erodes ~200nm
- Concept tested at UIUC (summer 2016) with favorable results
  - Bake-out flux and temperature simulated with H2O+CO2 bubbler – **NO REACTION**
  - Spectroscopy indicated highest Li/O ratio with capped layer

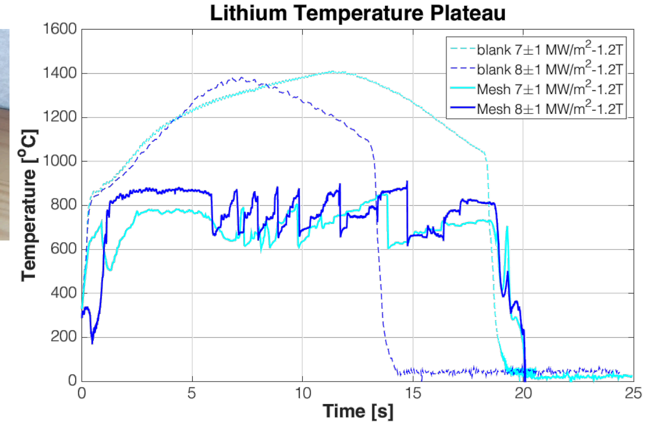




Power dissipation of Li pre-filled targets evaluated in MAGUM-PSI linear plasma device

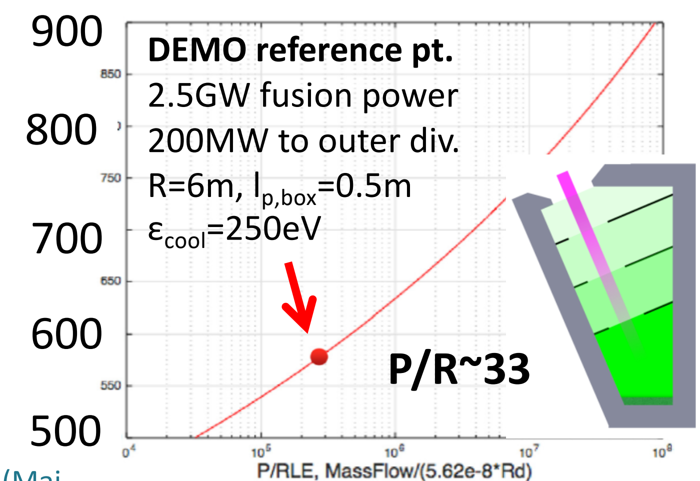
- Li-target tested based on pre-filled concept for NSTX tested in MAGNUM-PSI linear plasma device
  - Temperature clamping exhibited
  - Similar behavior for Liquid Sn target
  - Supports idea of power exhaust via Li vapor





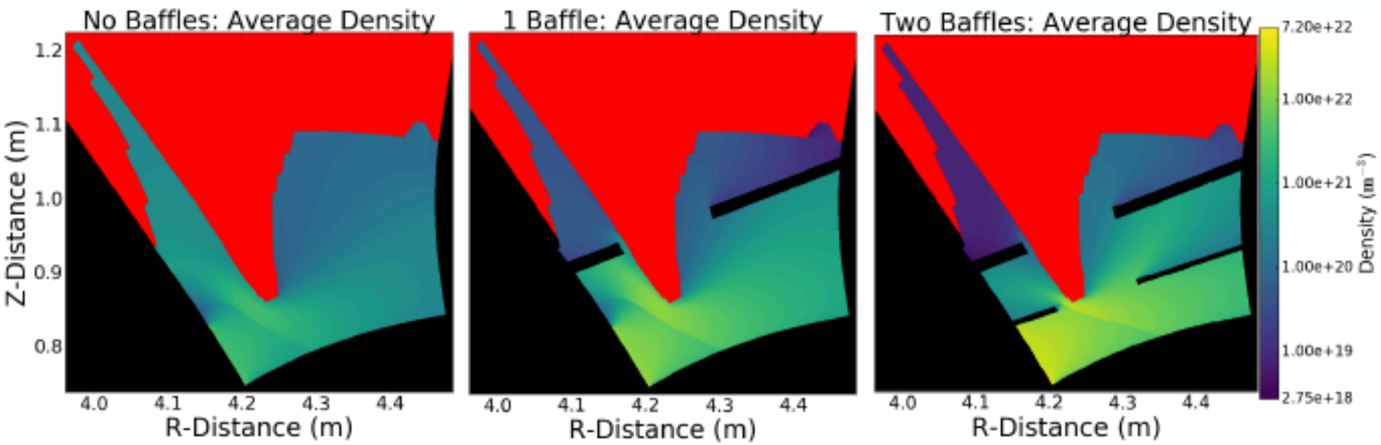
P. Rindt et al., *ISLA 2017*

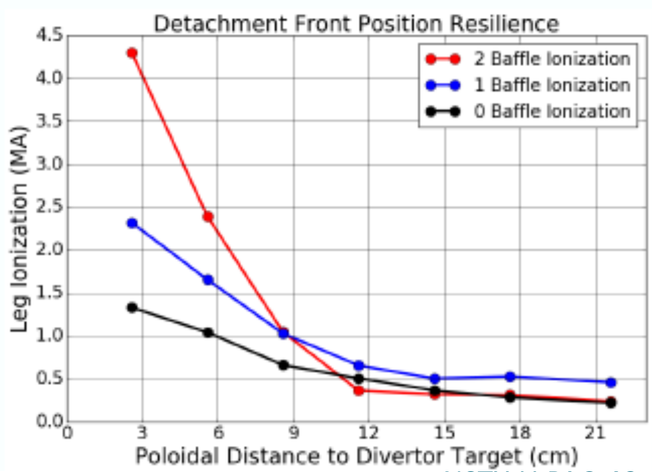
- Lithium vapor box 0D calculation indicates high power exhaust potential for DEMO



R. Goldston et al., *Nucl. Mater. Energy* **12** (2017) 1118

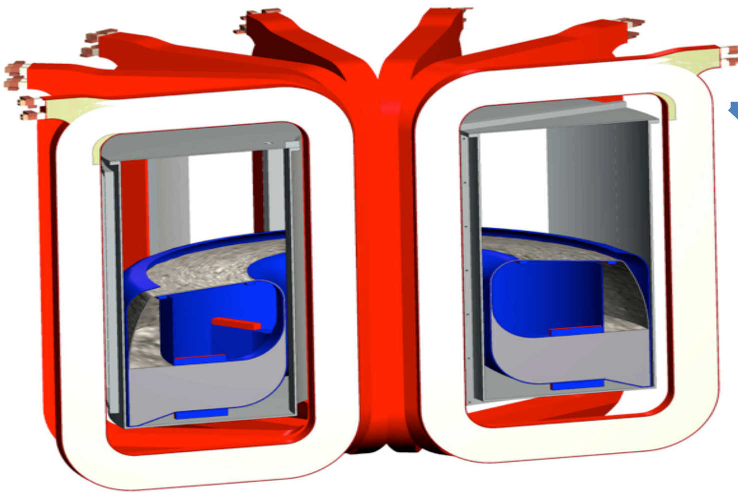
Power dissipation science via lithium vapor boxes being evaluated for FNSF

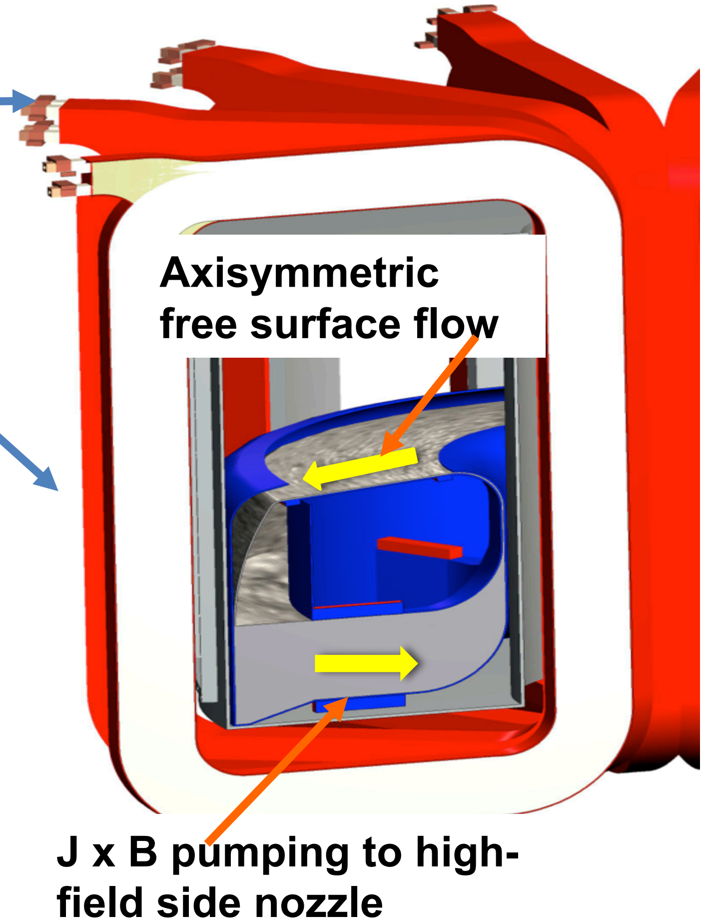




Baffles increase the localization of the lithium vapor, but even without them, private flux side evaporation gives a very strong variation of plasma cooling with position, indicating a resilient detachment front location.

Flowing Liquid Metal Torus (FLIT)





- Test axisymmetric liquid metal flows in toroidal fields in realistic B to show feasibility of fast LM divertor concept for NSTX-U at high heat fluxes
  - **Present: LDRD for design study, *construction is unfunded***
- Proof of principle R&D at PPPL:
  - **Develop the <u>engineering</u> for fast flow system (jxB pumps, nozzles – jets/open surface, etc)**
  - **Use Gallinstan (Ga, In, Sn); *No plasma in FLIT***

E. Kolemen, *Nucl. Mater. Energy* **19** (2019) 524