Pre-Conceptual Design of Liquid Li PFCs in NSTX-U

R. Maingi, E. Emdee, R. Goldston, A. Khodak PPPL

International ST Virtual Workshop, 2-Nov-2022

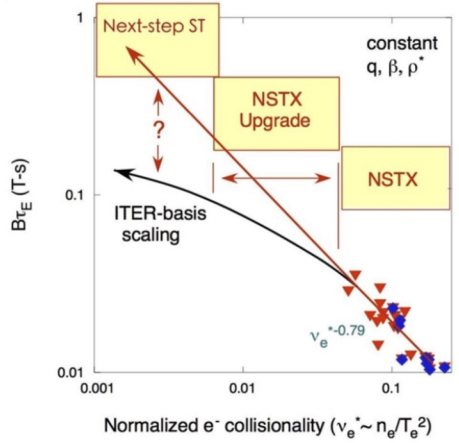
Three high-level Objectives comprise the mission-oriented NSTX-U research program

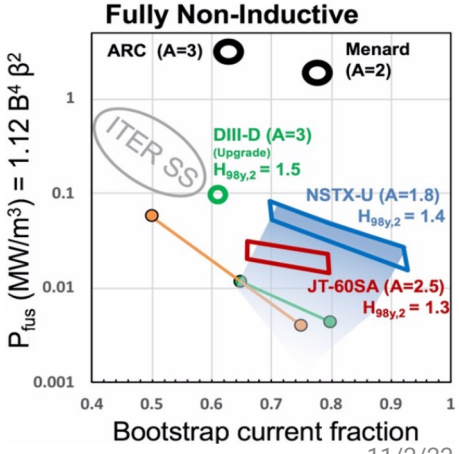
- Three high-level Objectives comprise the mission-oriented NSTX-U research program

1. Extend confinement and stability physics basis at low aspect ratio and high beta to lower collisionality
   - Enhanced confinement necessary for FPP (of any aspect ratio)
   - Does good ST confinement extend to low collisionality?

2. Develop non-inductive (NI) operation at high-performance and low-disruptivity
   - Steady-state compact ST fusion devices require enhanced confinement, NI operation
   - Develop unique high-beta, strong shaping route to NI operation

3. Develop and evaluate conventional and innovative power and particle handling techniques
   - NSTX-U designed for 8 MW/m^2 for 5 s; can access 50-100 MW/m^2
   - Research will also inform next 5YP





NSTX-U LM PFC designs build on a US program that has identified LM PFC design windows for a Fusion Nuclear Science Facility

- **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, ….

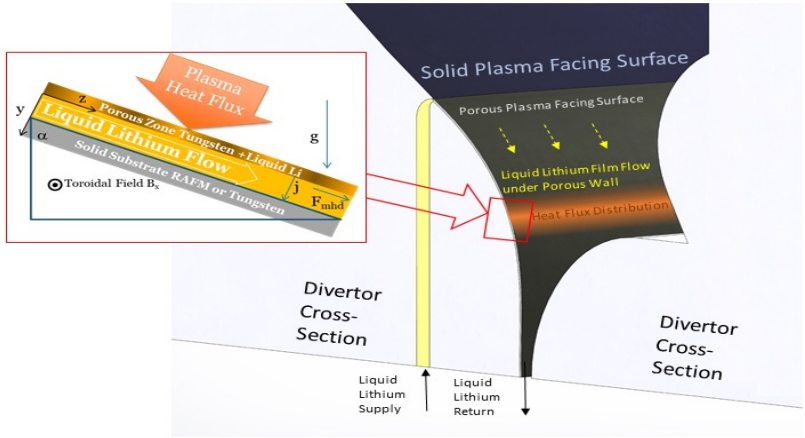
- A design window to operate liquid Li divertor PFCs with low evaporation (i.e. < 450 ^{o}C) has been identified for a simplified FNSF geometry
  - Self-consistent between LM MHD, heat transfer and plasma modeling
  - Required Li PFC flow speeds ~ 5-15 m/s
  - Two options: a LM jet with high initial speed, and j x B driven flow
  - Li retained in divertor: upstream Li concentrations $\leq$ 1% up to 10^{23} Li flux

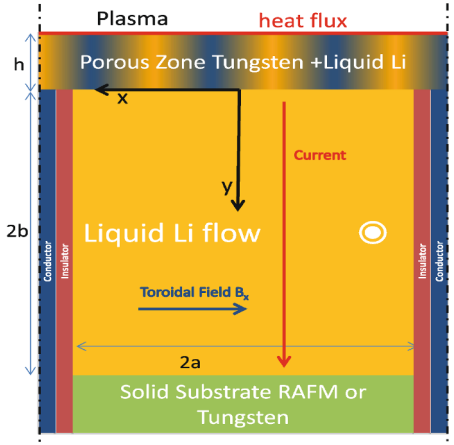
➢ NSTX-U Liquid Li PFC designs use concepts developed in the FNSF design

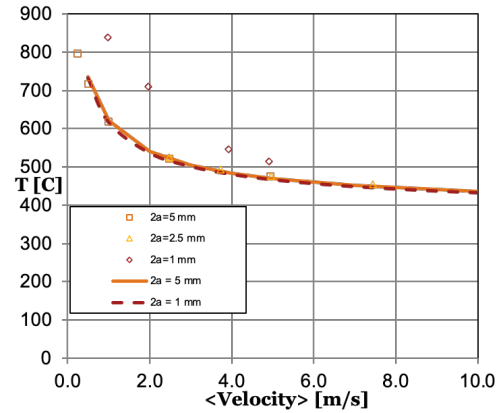
Flowing liquid Li PFC analyzed for FNSF being evaluated for NSTX-U

- Capillary porous system using j x B flow drive (**CPSF**) can remove 10 MW/m^2 with T_{surf} < 450 ^oC
  - Required flow speed ~ 7 m/s
  - Slower flow speeds allow surface temperature to rise, bordering on evaporative solutions (Li vapor)

- MHD pumping 'cost' < 10% of incident heat flux for flow speeds < 10 m/s

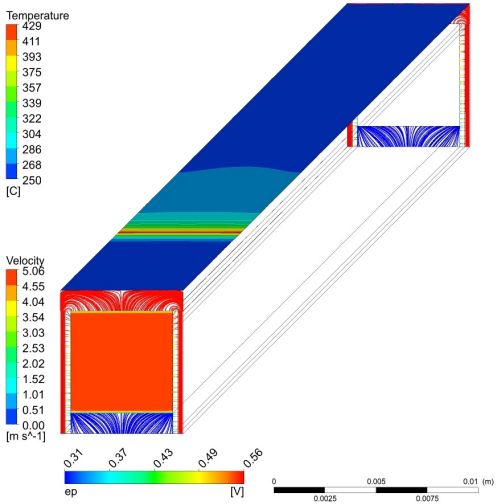


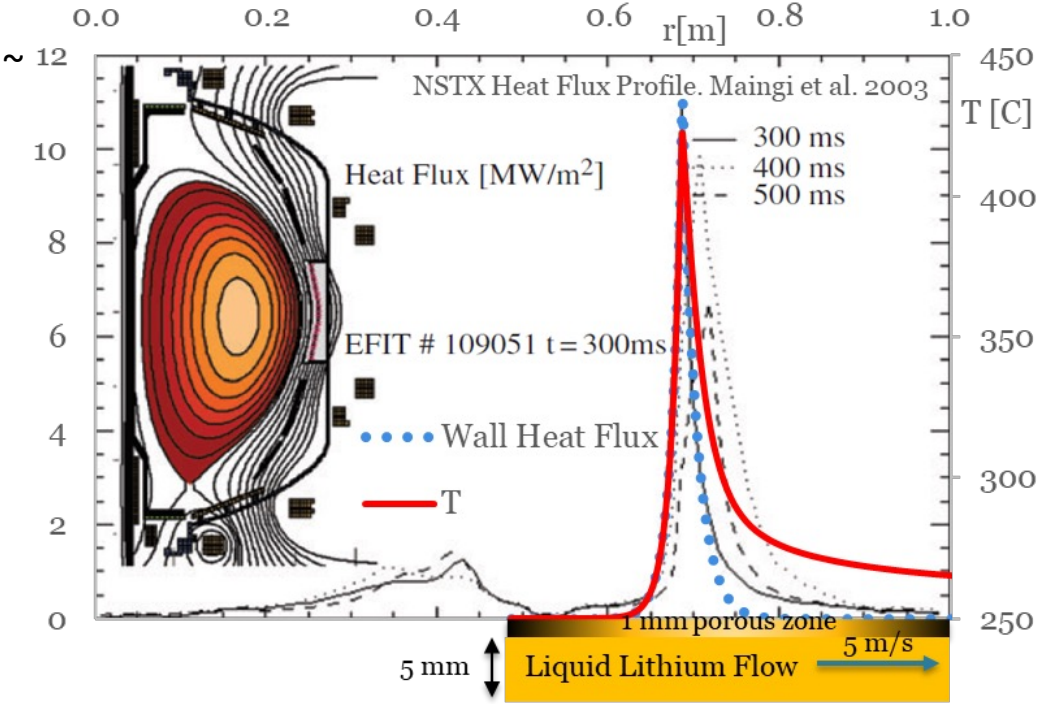




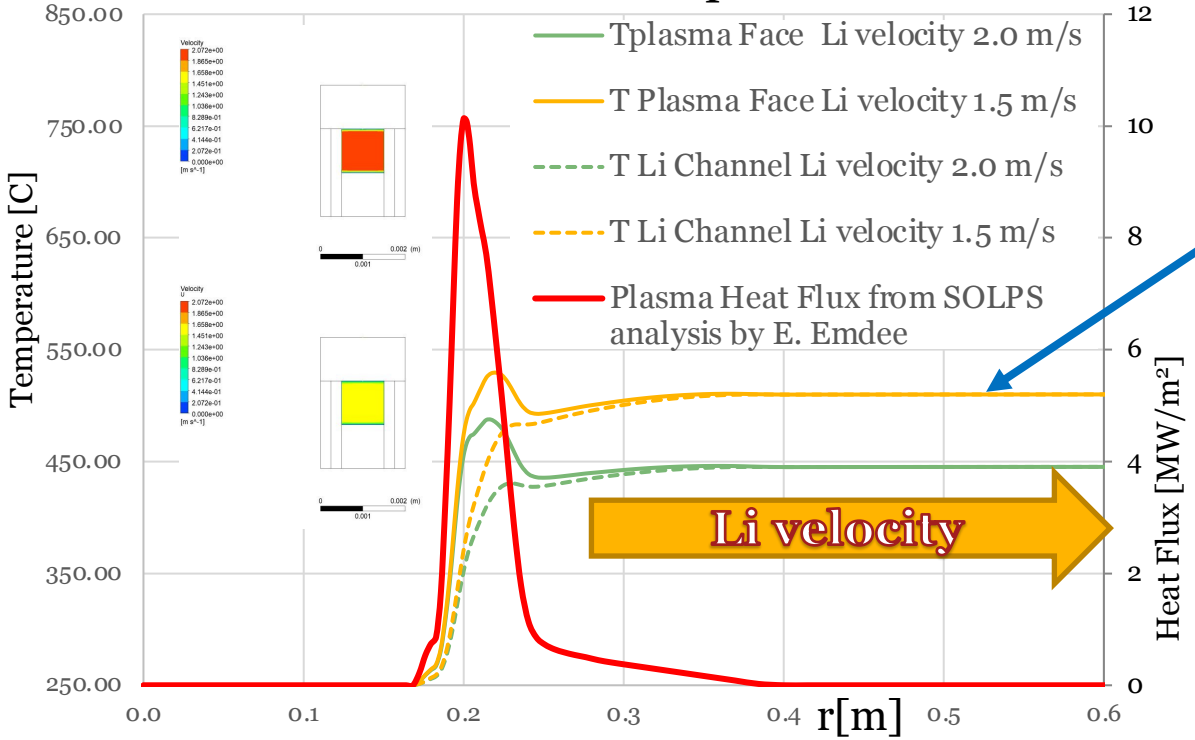
CPSF concept simulated with NSTX heat flux profile

- Computational Fluid Dynamics analysis using CFX
- 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





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

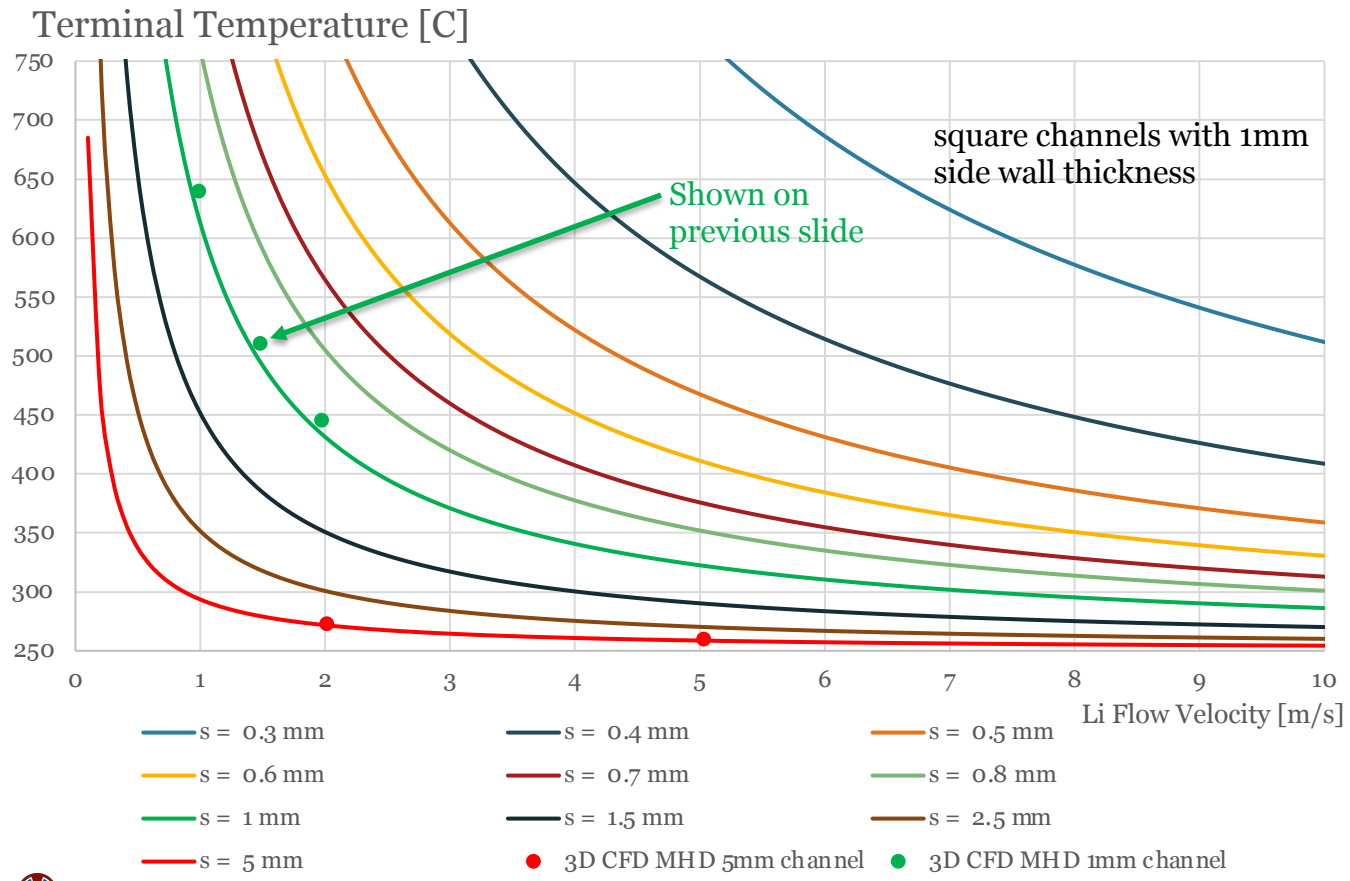


1mm square cross-section channel with 1mm porous wall provides constant temperature distribution on plasma surface ~500C at 1.5 m/s
This temperature level is targeted by Vapor Box divertor System

Temperature level is defined by:

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

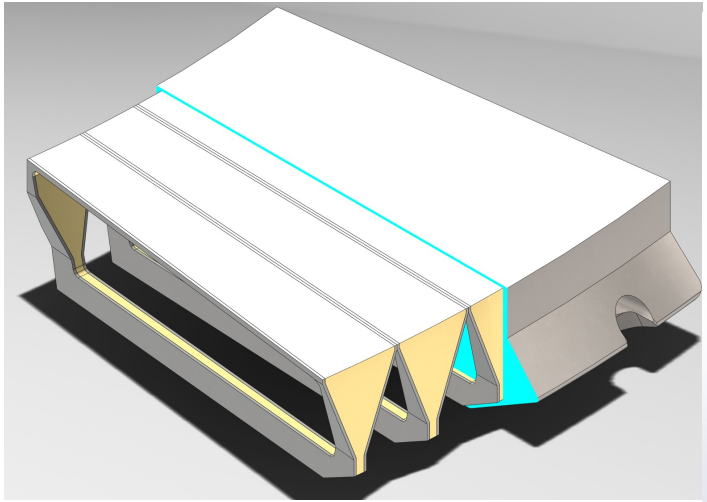
Parametric studies define parameters of CPSF System



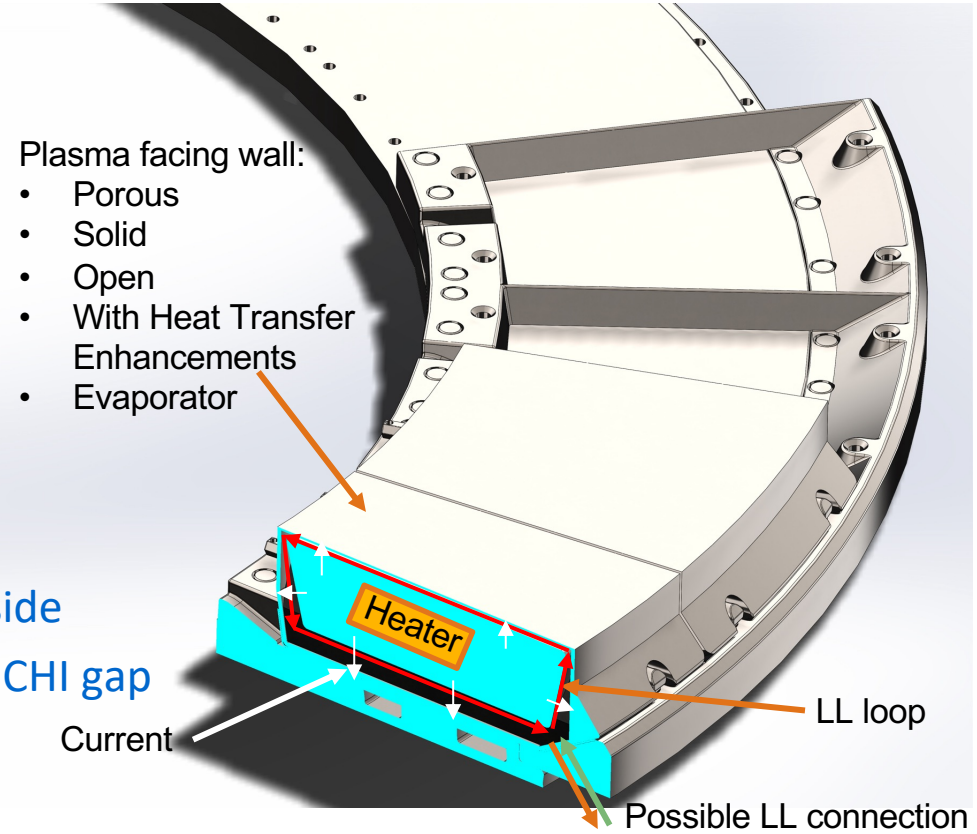
~500C temperature level is currently targeted by Vapor Box divertor System

Analytical Model Result are confirmed by CFD analysis

Implementation Concept NSTX-U Inboard divertor tile replacement



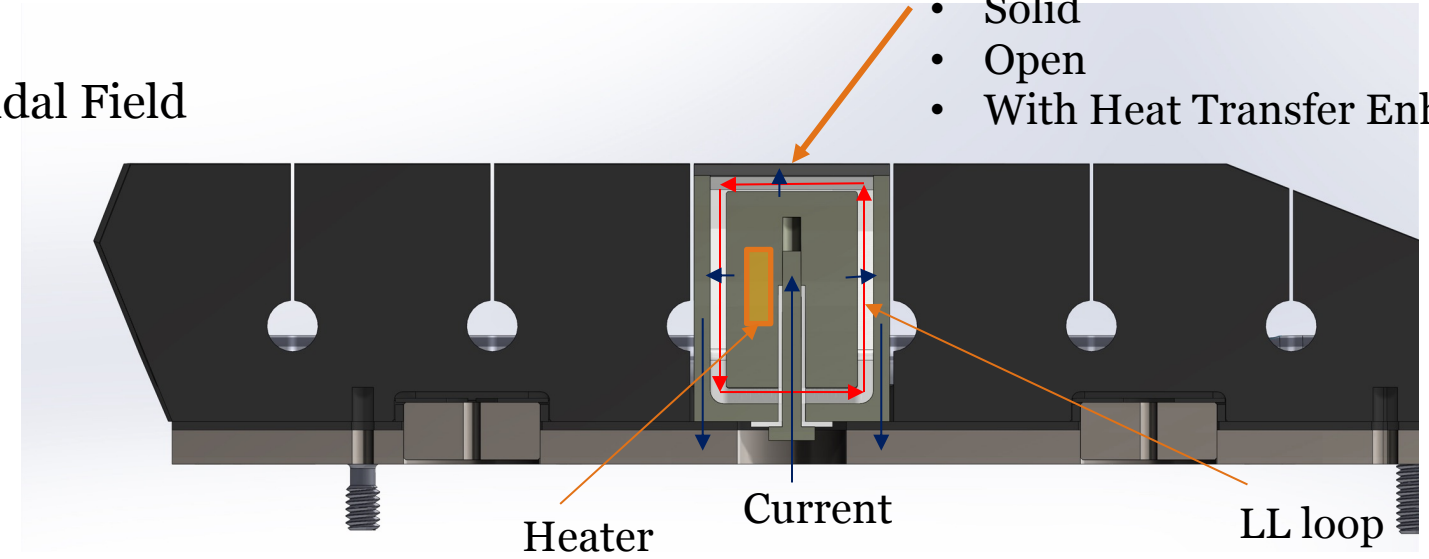
- Tile with 5 LL loops
- Electric heater incorporated inside
- Possibility of LL supply through CHI gap



Minimalistic concept: tile with insert

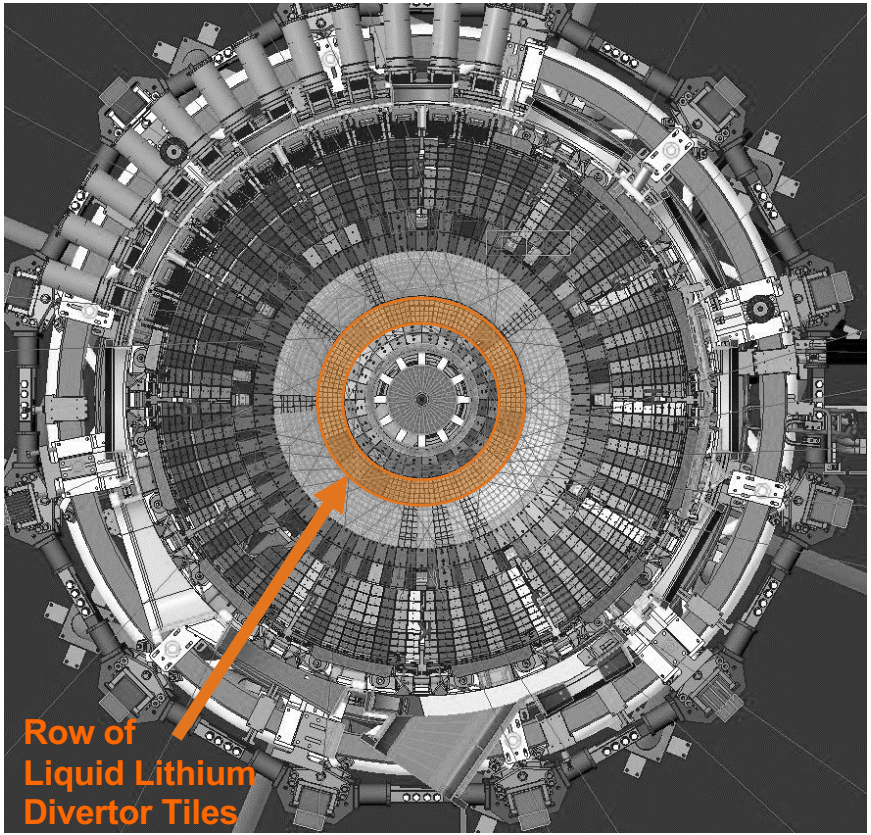
Plasma facing wall:
- Porous
- Solid
- Open
- With Heat Transfer Enhancements

Toroidal Field



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

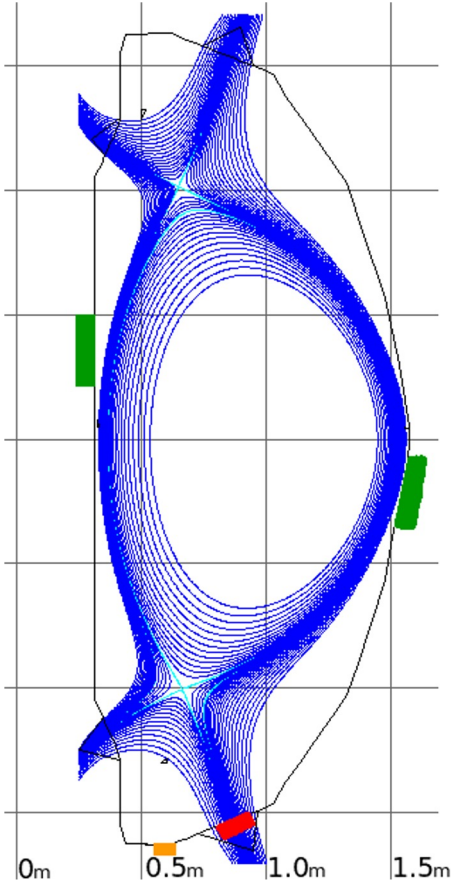
Proposed Row of NSTX-U Divertor Tiles with Liquid Lithium



Li vapor box design calculations for NSTX-U with SOLPS/ITER

- Start with NSTX-U discharge and project for high NBI
- Set cross-field transport to get λ_q close to Goldston HD scaling
- Add in gas puffs on the private region and common flux regions to drive puff and pump type SOL flow

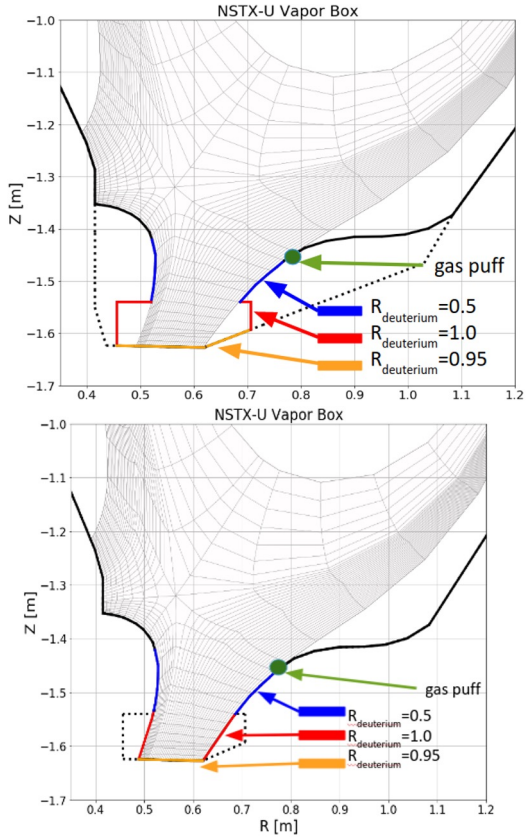
NSTX #204202
Green, orange: gas puffs
Red: Li evaporation



E. Emdee et al., *NME* **27** (2021) 101004

Progress in lithium vapor box design calculations NSTX-U

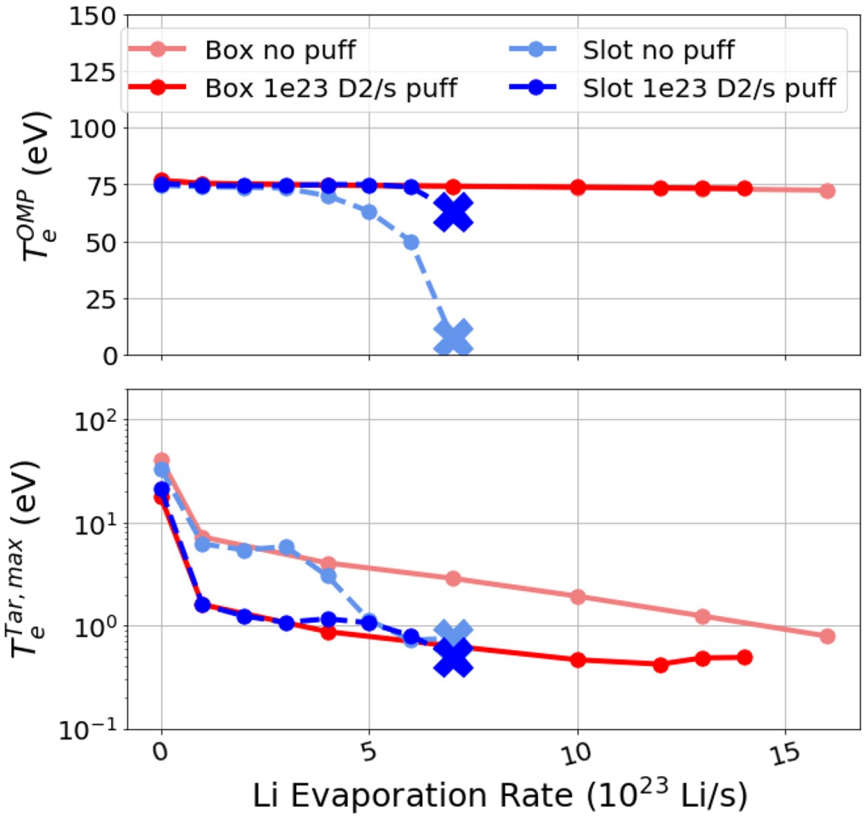
- Start with NSTX-U discharge and project for high NBI
- If there are no baffles, Li migrates upstream along the outer side far SOL
  - Adding baffles reduces Li leakage
  - Adding upstream D2 gas puff reduces Li leakage
- Making a box around outer strike point reduces Li leakage



E. Emdee et al., *NME* **27** (2021) 101004

Progress in lithium vapor box design calculations NSTX-U

- Start with NSTX-U discharge and project for high NBI
- If there are no baffles, Li migrates upstream along the outer side far SOL
  - Adding baffles reduces Li leakage
  - Adding upstream D2 gas puff reduces Li leakage
- Making a box around outer strike point reduces Li leakage
  - T_e^{OMP} preserved with box



E. Emdee, Ph.D. 2022

Many extra runs conducted for Lithium Vapor Box design for NSTX-U

- Cross-field transport coefficients reduced: λ_q closer to Goldston HD model prediction for NSTX-U, unmitigated q_{peak} from 65 – 92 MW/m^2
- Compared common flux and private flux region D gas puff to retain Li in divertor: PFR more effective
- Target recycling coefficient scanned: increasing R reduces required D gas puff for Li retention in divertor
- Input power scan: LVB resilient to power changes

NSTX-U LM PFC designs build on a US program that has identified LM PFC design windows for a Fusion Nuclear Science Facility

- A fast-flowing liquid Li PFC with speeds ~ 5 m/s can exhaust 10 MW/m^2 incident heat flux with T_{surf} < 450 C
  - Allowing T_{surf} > 500 C allows accesses evaporative regime akin to Li vapor box
- Li vapor box design calculations show the ability to reduce from 65-92 MW/m^2 to ~ 5-15 MW/m^2
  - Core Li concentration < 2-7%
- Synergy between combined Li vapor box with fast flow CPSF at bottom to keep Li clean/fresh

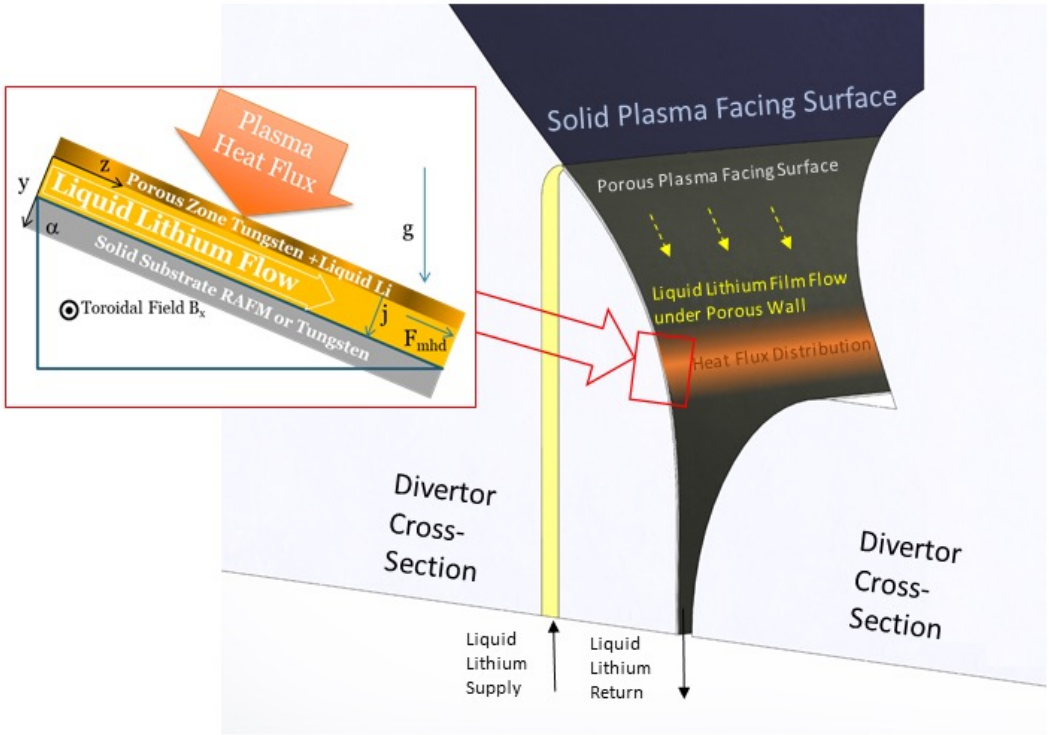
Next steps: validate design calculations by testing of these concepts

- The jxB driven fast flowing LM PFC design needs testing
  - Builds on jxB driven flow via midplane-inserted liquid Li limiters in EAST (4 generations), and 2 types in HT-7 before that
  - Builds on experiments with Li-based, 3-D printed Capillary Porous Systems on MAGNUM-PSI, led by Peter Rindt
- The Li vapor box needs testing
  - Is design compatible with a fast flow system in the bottom of the box
- Practical issues to keeping Li clean in a porous system with normal vacuum conditions need to be resolved (refilling, flow stoppage…)

Thank you for your attention

Liquid Lithium Cooling System with Porous Wall (CPSF)

- Liquid metal is controlled by the solid porous structure, creating a smooth surface that can be shaped to minimize the heat flux density
- The porous structure provides liquid Li on the plasma facing wall, allowing particle pumping in the case of low surface temperature liquid Li, and evaporative cooling in the case of disruption and other high heat flux transient events
- Liquid Li which also acts as a coolant is flowing along the heated wall in the amount sufficient to remove most of the incoming heat
- Liquid coolant is propelled along the wall by gravity or MHD pumping
- The porous wall is placed on top of the liquid coolant, and a non-uniform energy flux from the plasma is applied on the porous surface



A. Khodak and R. Maingi, Physics of Plasmas **29**, 072505 (2022); https://doi.org/10.1063/5.0088015

A. Khodak and R. Maingi, Nuclear Materials and Energy 26 (2021) 100935 https://doi.org/10.1016/j.nme.2021.100935