SOLPS Simulations of Lithium Heat Flux Mitigation and Particle Flows in NSTX-U

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NSTX-U Research Meeting

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Education and Research Experience

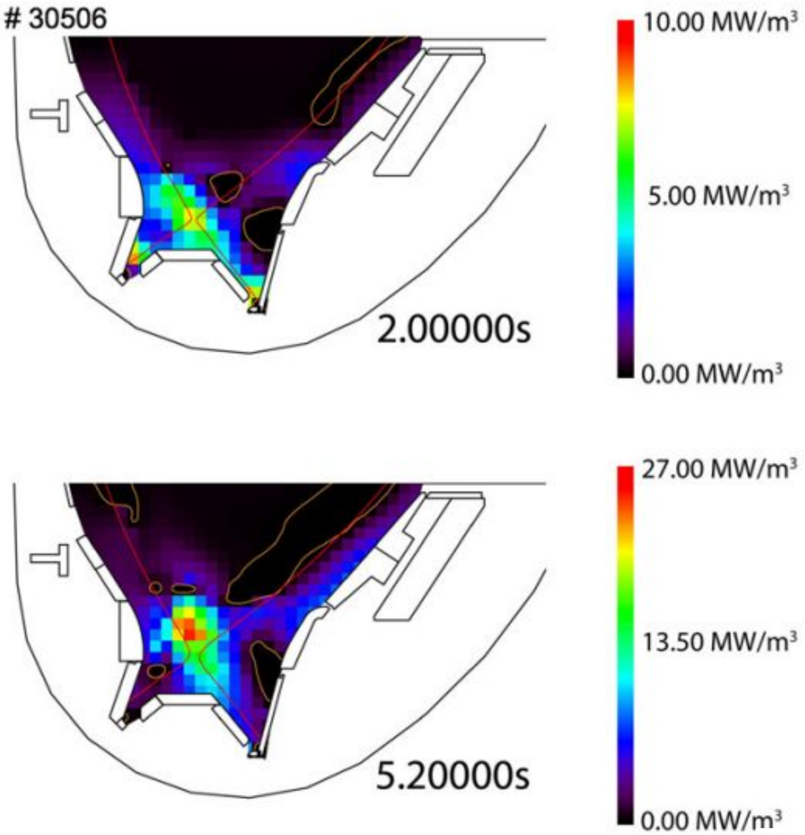
- University of California Davis (2012-2016)
  - Superfluid Helium Vortices
  - Aerospace Corporation Microelectronics Division
  - Large Underground Xenon dark matter detection experiment
- Princeton University (2016 - Expected August 2022)
  - Modelled the lithium vapor box divertor

Publications

- **J.A Schwartz** et al Review of Scientific Instruments 89 (2018) 10J113
  - Magnum-PSI vapor box experiment design using DSMC
- **J.A Schwartz** et al Nuclear Materials and Energy 18 (2019) 350-355
  - DSMC calculations to measure H_2 trapping in Magnum-PSI experiment
- **E.D Emdee** et al, Nuclear Materials and Energy 19 (2019) 244–249
  - DSMC calculations of the effect of vapor box baffling in FNSF
- **T.D Rognlien** et al Nuclear Materials and Energy 18 (2019) 233-238
  - UEDGE comparison with DSMC calculations above
- **E.D. Emdee** et al Nuclear Fusion 59 (2019) 086043
  - DSMC calculations of how to simplify the FNSF vapor box geometry
- **E.D. Emdee** et al Nuclear Materials and Energy 27 (2021) 101004
  - SOLPS calculations of lithium evaporation in NSTX-U geometry
- **W. Guttenfelder** et al (2022) 62 042023
  - NSTX-U overview

Introduction: Divertor Detachment Can Be Problematic

- Divertor detachment is necessary for future fusion devices to ensure PFC lifetime
- Divertor detachment with medium-Z impurities has the tendency to create a highly radiating region at the X-point
  - Can reduce pedestal performance
  - Confinement can be maintained at the cost of high Z_{eff}
- Goal: create a detached divertor that confines radiation and impurities close to the target



A. Kallenbach *et al* 2015 *Nucl. Fusion* 55 053026

Introduction: The Lithium Vapor Box

- The lithium vapor box seeks to detach via lithium vapor evaporation near the target, and condensation further upstream

- Original vapor box design imagines different chambers for condensation and evaporation

- A large focus of this work is determining the importance of the specific geometry

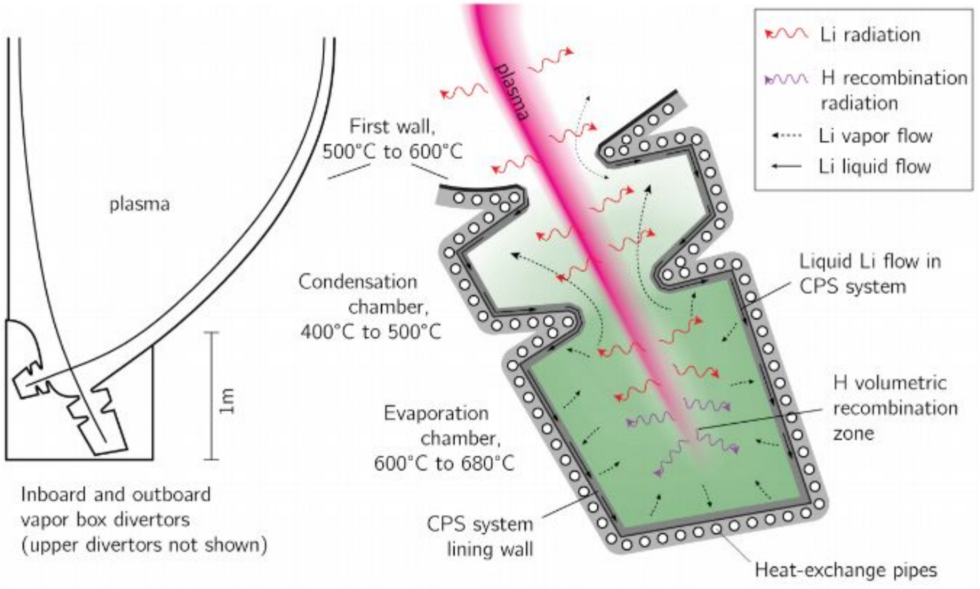


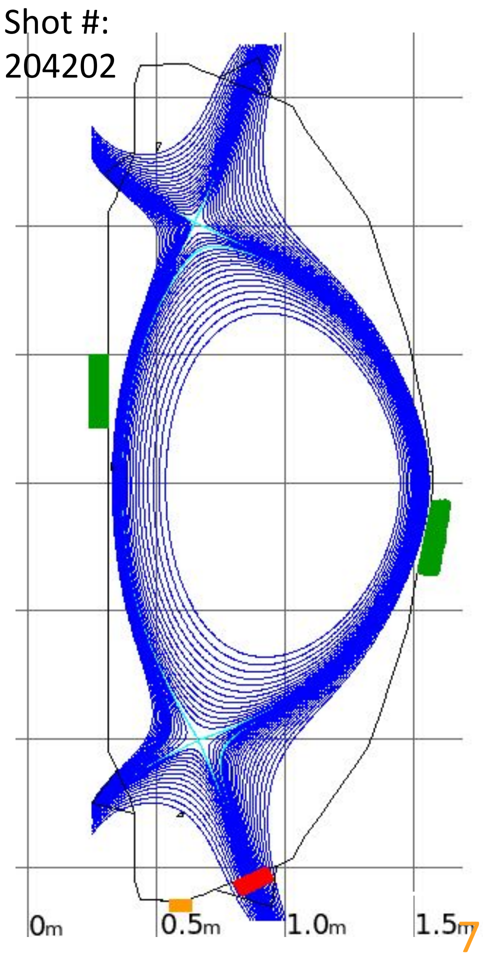
Diagram Credit: Jacob Schwartz

Outline

- Introduction
- The Lithium Vapor Box at low power
  - Detachment & Upstream Ionization Source
  - Using baffles
- 65 MW/m^2 Mitigation
  - Slot vs Box Geometry
- Sensitivity Tests
  - Recycling Coefficients
  - Transport Coefficients
  - Puff Location

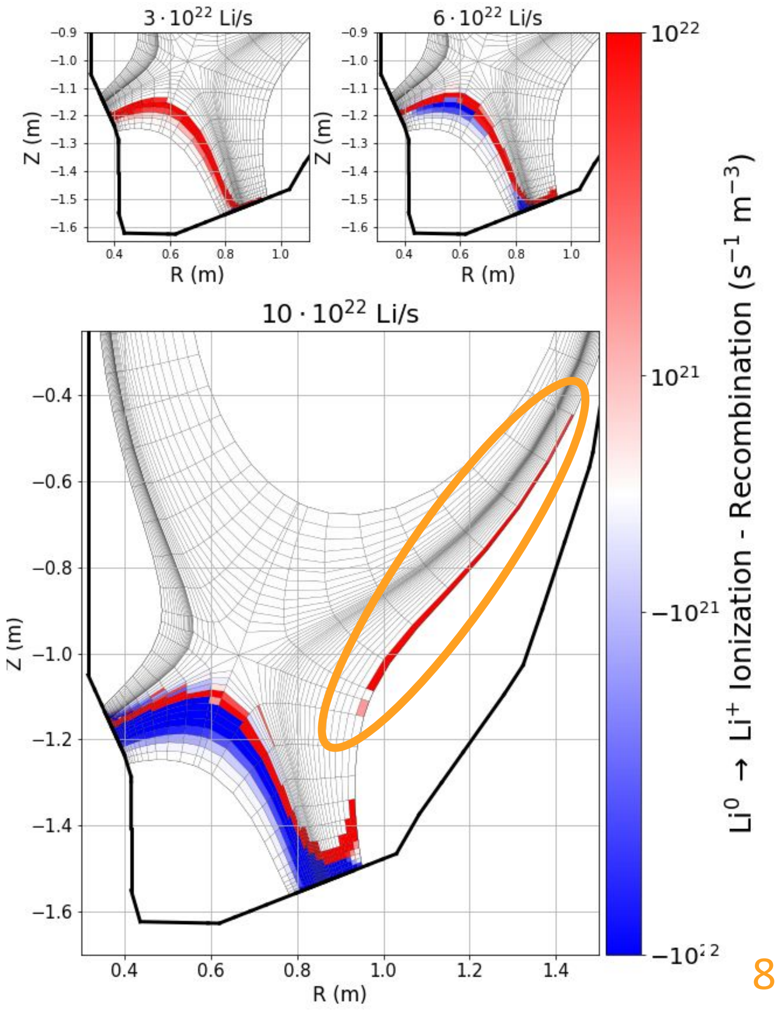
The Lithium Vapor Box is first modelled at Low Power/No Baffles

- Using SOLPS-ITER to get accurate picture of upstream plasma contamination
  - No E x B drift at present
- Used NSTX-U magnetic equilibrium and current NSTX-U PFCs as an example
- D_2 gas puff locations shown in green and orange
  - Green locations are in experiment and used in profile matching
  - Orange is added in Private Flux Region (PFR) for predictive simulations
- Lithium evaporator location in red
- 2 MW of input power
- 1.5×10^{19} m^{-3} at core boundary



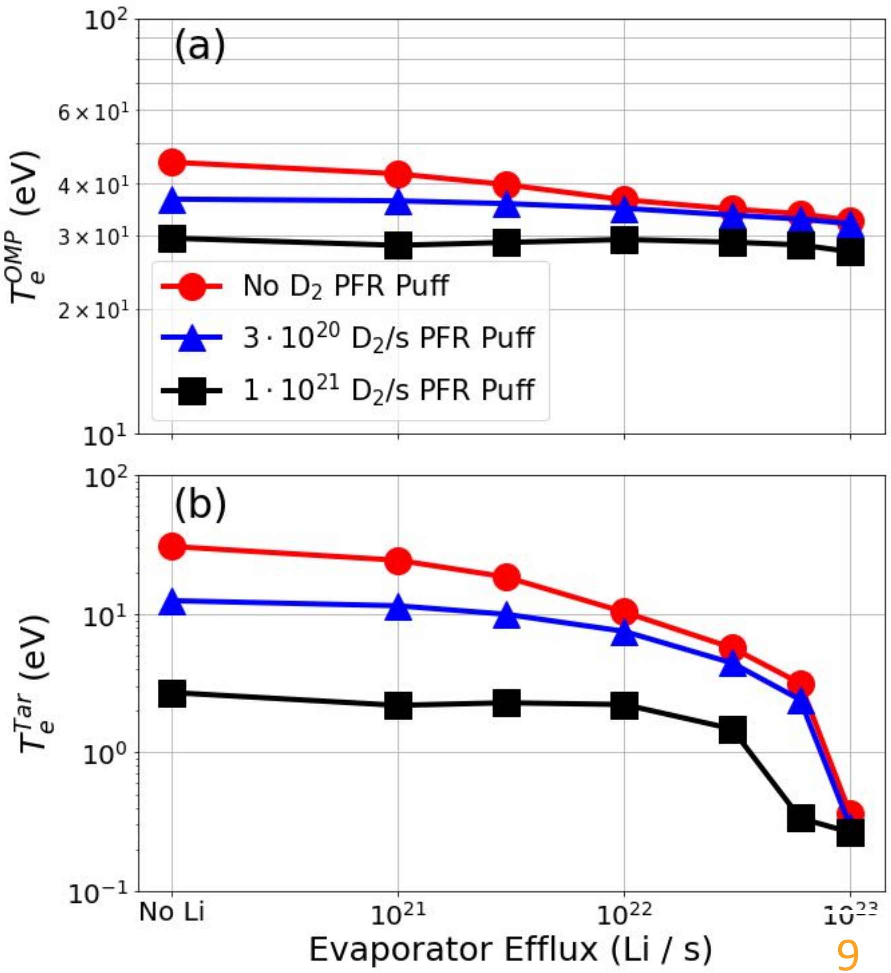
Ionization Fronts Show Poor Li^0 Containment

- Detachment is evident by the formation of a lithium recombination zone near the target
- But upstream ionization is a problem due to poor lithium vapor containment



Effect on Temperature

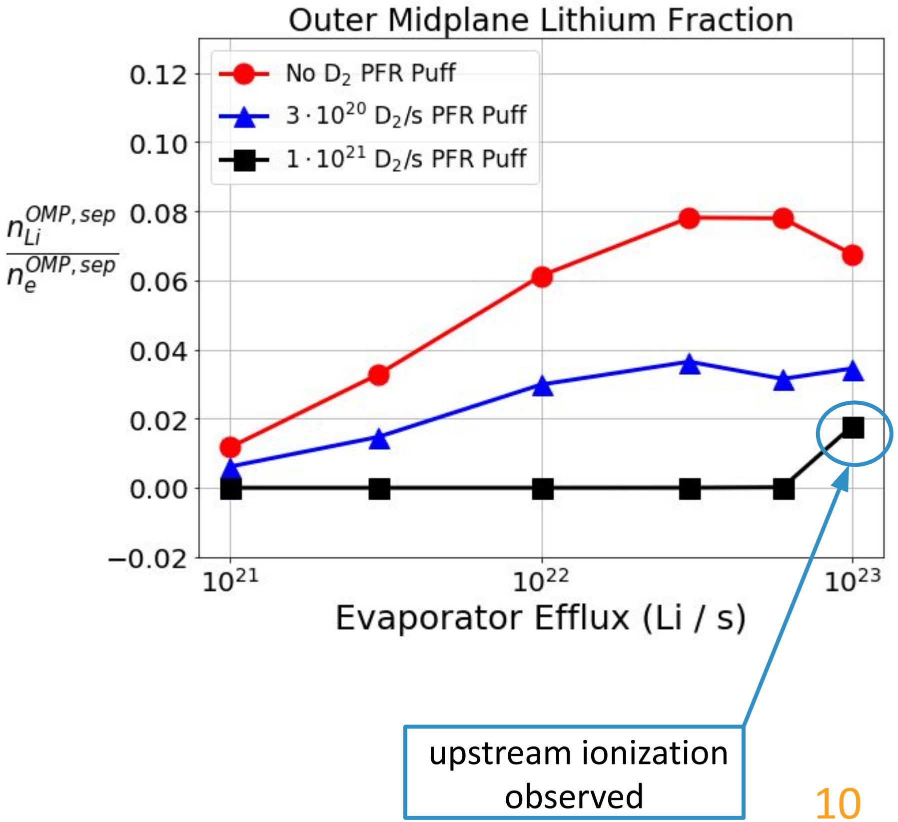
- OMP separatrix temperature affected by lithium vapor evaporation and D_2 puffing
- Target temperature drops precipitously once ~10^{23} Li/s is evaporated
- < 1eV T_e^{Tar} is associated with detachment



Lithium Fraction Reduced by D-Puff

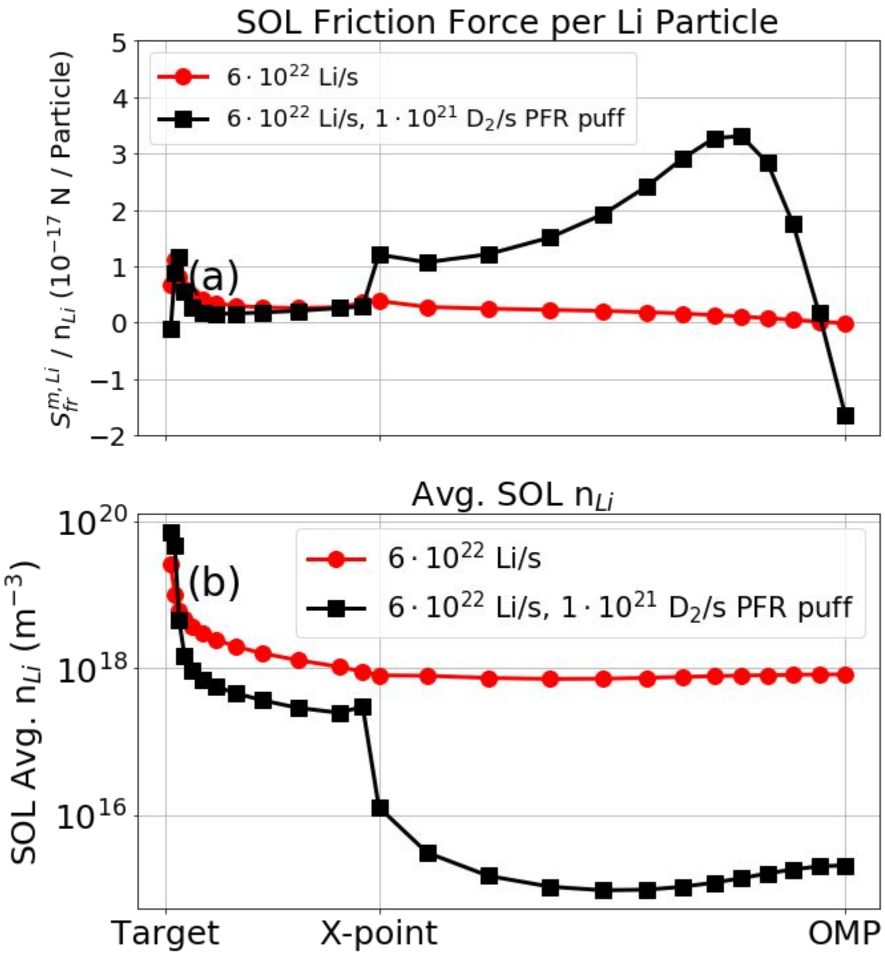
- The lithium fraction is strongly dependent on the amount of D_2 puffed in, allowing the lithium fraction to be effectively controlled.

- Upstream ionizations caused the 10^{23} Li/s case to have non-negligible lithium at the OMP, regardless of D_2 puff



Friction Forces Restrain Li Below X-Point

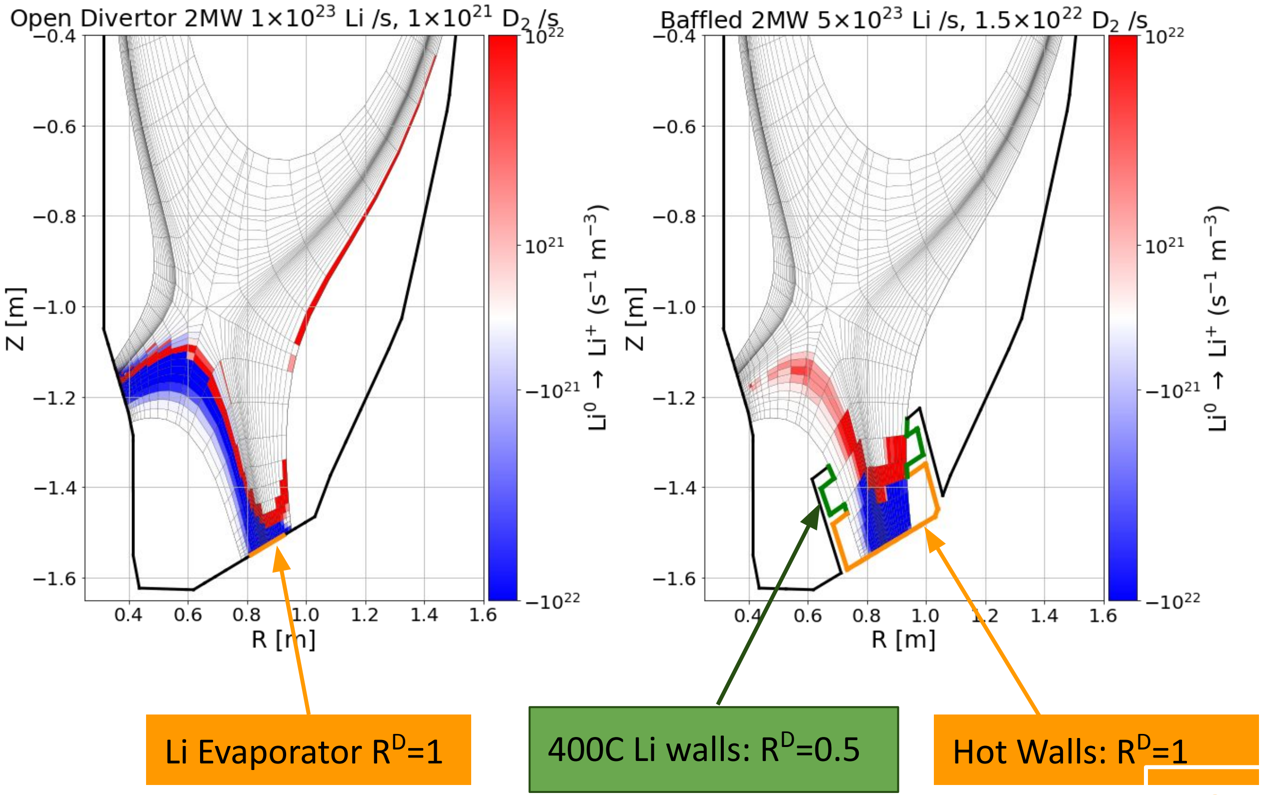
- The average friction force acting on an Li particle and the resulting density of Li averaged across the SOL flux tubes
- This is evidence of a 'puff and pump' effect whereby the ion friction force pushes the impurities towards the divertor plate, ensuring the upstream plasma is uncontaminated.



Emdee et al. Nuclear Materials and Energy 27 (2021) 101004

Closure Reduces Upstream Ionization

- Closing divertor removes the upstream ionization even at higher levels of divertor detachment
- Midplane lithium fraction ($n_{Li\ ions}/n_e$) goes from ~2% to ~0.01% for the same upstream temperature



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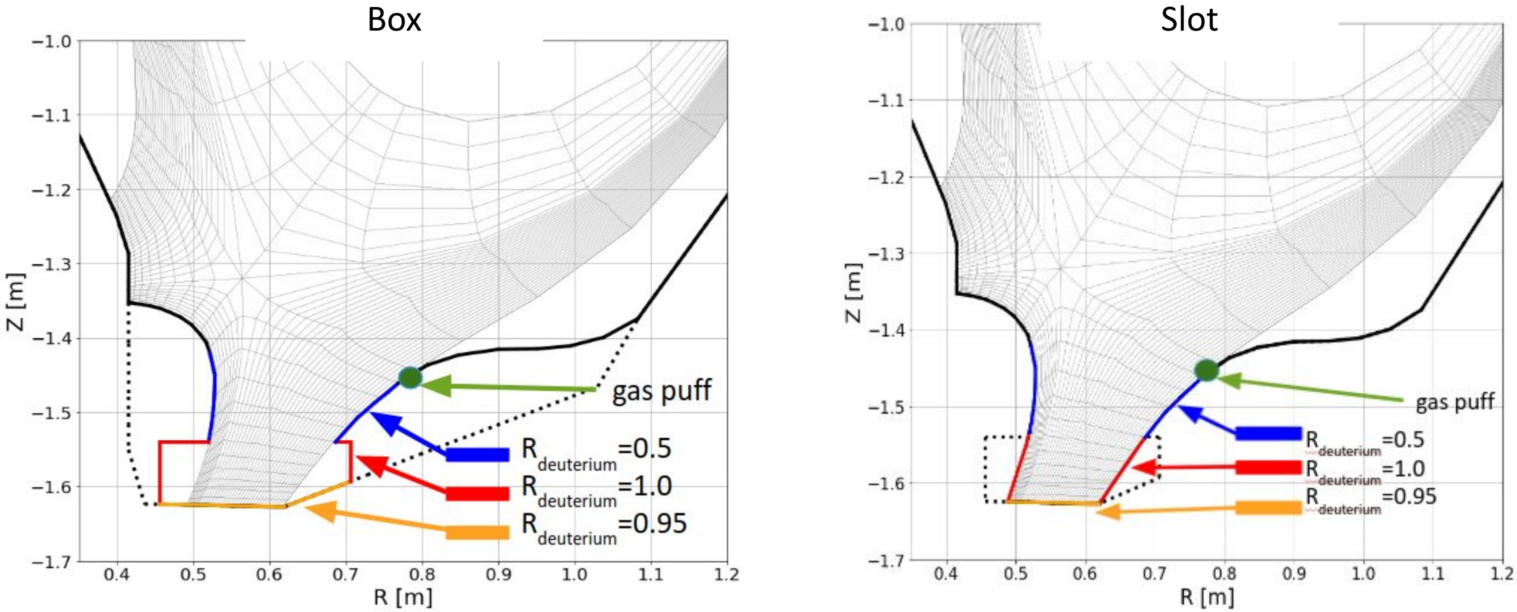
  - Puff Location

Next: Model High Power Conditions

- Low power lithium vapor box can have nearly non-existent upstream lithium fraction if the divertor is closed to prevent upstream ionization
- Moved to predictive modeling of high power NSTX-U H-mode shots
  - P_{in} = 10 MW
  - q_{target}^{max} ~ 65 MW/m^2
  - λ_q ~ 4.8 mm

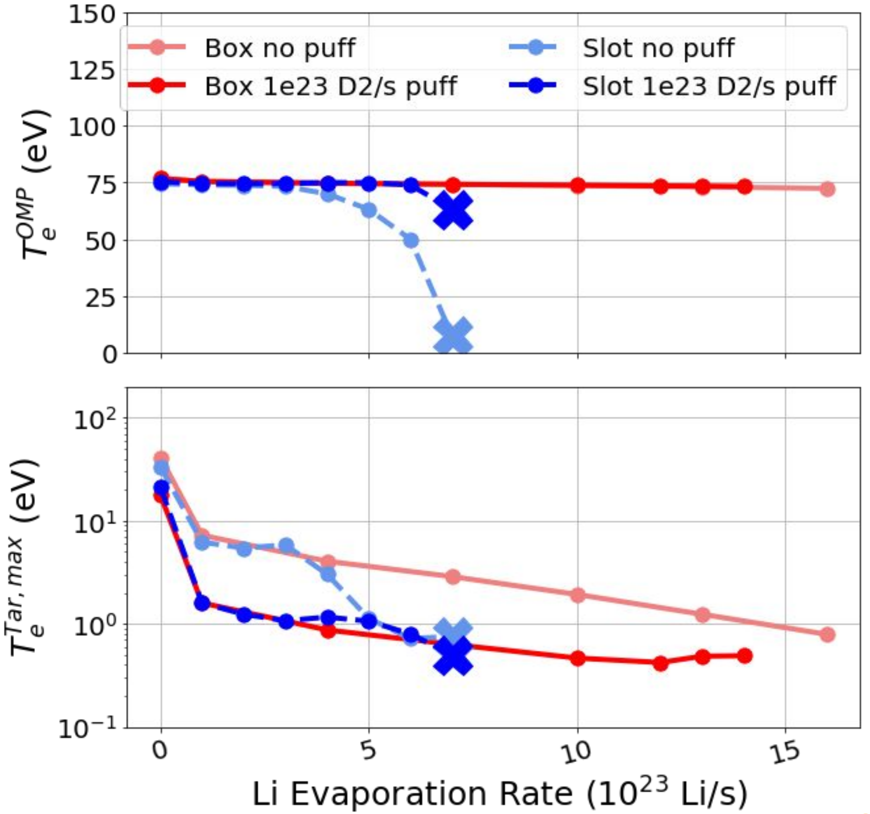
Set Up: Box to Slot Comparison

- Set up two divertor designs, one closer to the original vapor box design with a set of baffles and one a slot divertor geometry



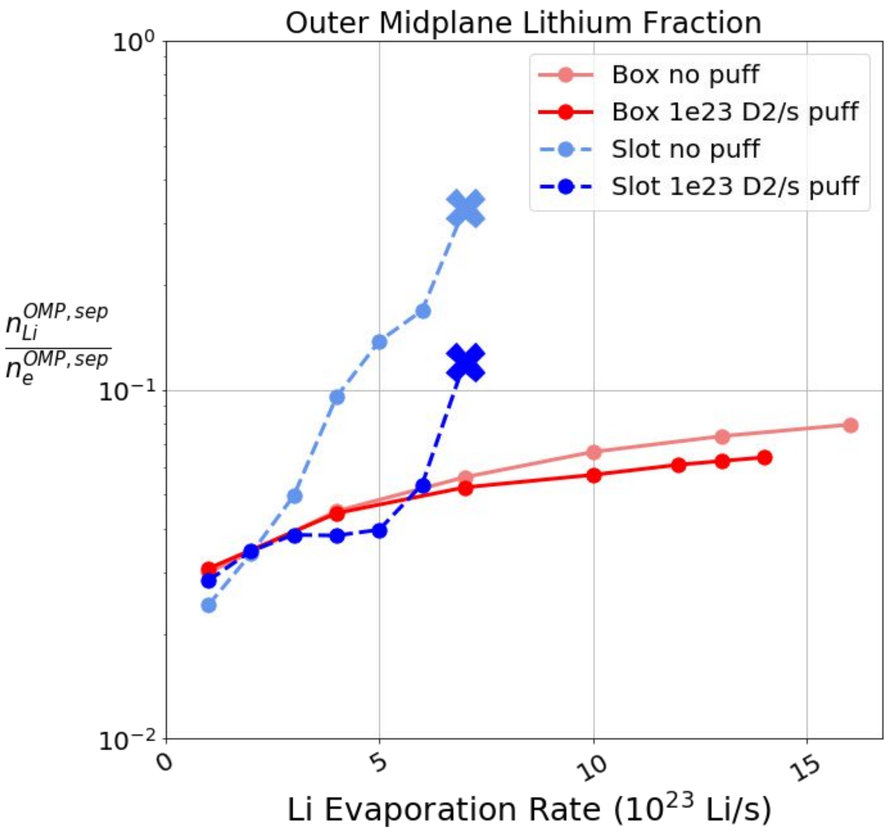
Upstream Temperature Can Be Sustained At High Puff Rate

- The upstream temperature is unaffected lithium evaporation if diverter is baffled
- Slot sees upstream temperature degradation as lithium evaporation is increased
  - Corresponds to $n_{Li}/n_e > 0.1$ upstream



Lithium Fraction Controlled Better in Box

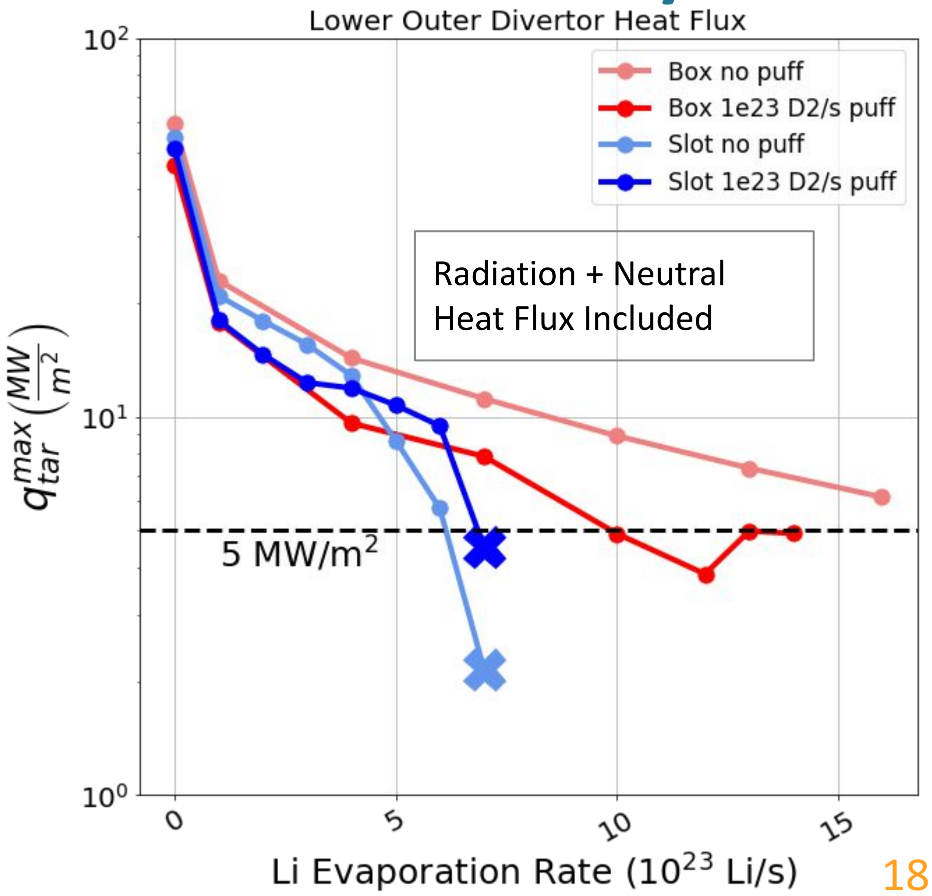
- Upstream lithium content in the slot geometry is less controlled
- The baffles are important for lithium containment



Divertor Heat Flux Dramatically Reduced

- Slot has difficulty getting below 5 MW/m^2 without reductions in upstream temperature

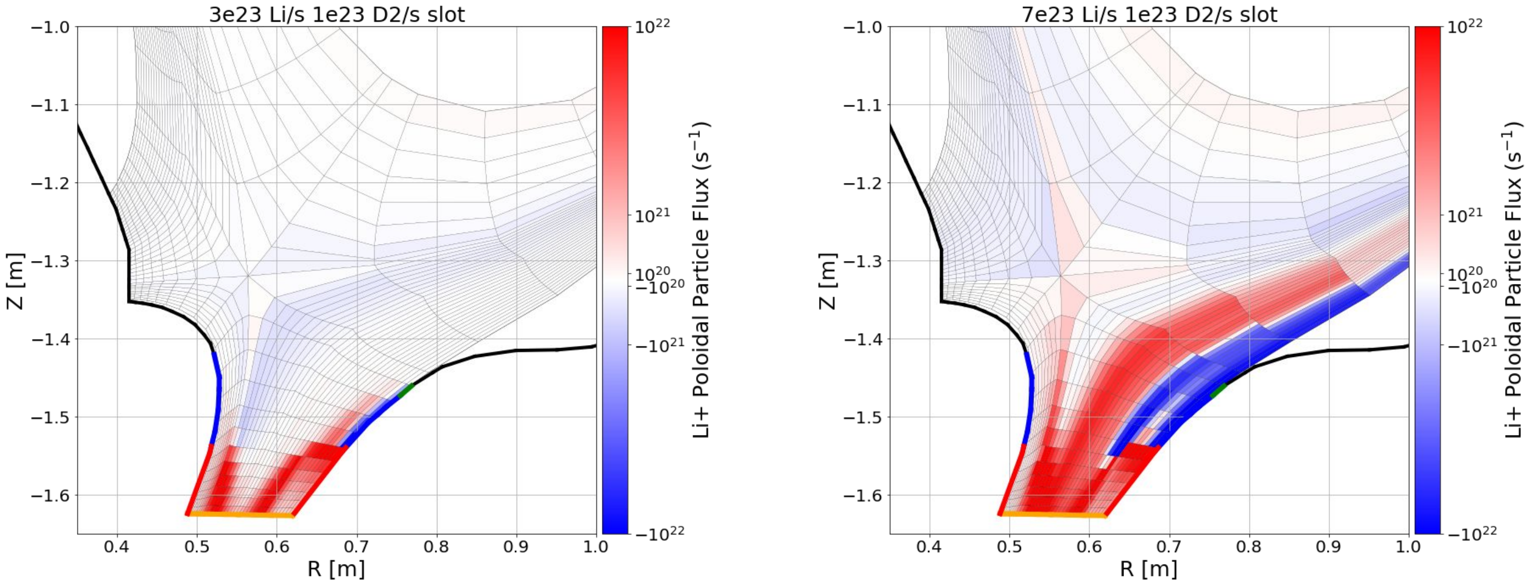
- Box can contain the lithium and reduce heat to the target further



Flow Reversal in Far SOL in Slot Geo.

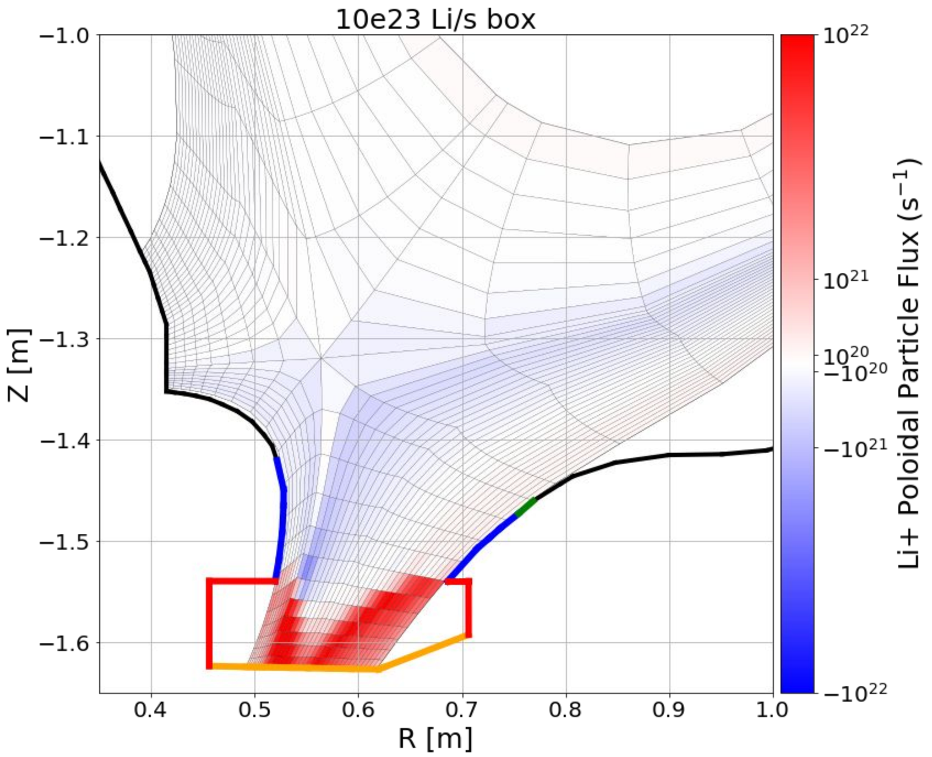
- The far SOL lithium flow eventually becomes upstream-directed with enough lithium evaporation in the slot

Downstream-directed Li Flow
Upstream-directed Li Flow



Flow Never Reverses in Box Geo.

- In the box geometry the far SOL lithium flow is never reversed for any of the cases tested



Good Scenarios Are Available For Both Slot and Box for q_{tar}^{max}<10MW/m^2

- Best case with 10^{23} D_2/s
  - Slot
    - 6 x 10^{23} Li/s
    - q^{max}_{target}=9.5 MW/m^2
    - $(n_{Li}/n_e)^{OMP,sep}$ = 0.053
  - Box
    - 4 x 10^{23} Li/s
    - q^{max}_{target}=9.6MW/m^2
    - $(n_{Li}/n_e)^{OMP,sep}$= 0.044

OR

- 10 x 10^{23} Li/s
- q^{max}_{target}=4.9 MW/m^2
- $(n_{Li}/n_e)^{OMP,sep}$= 0.056

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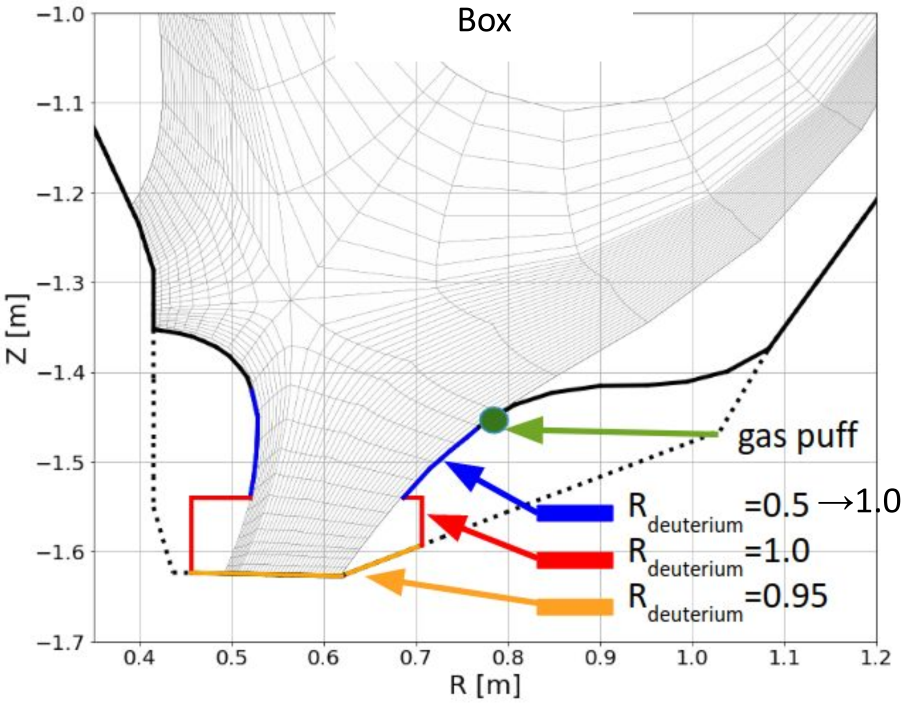
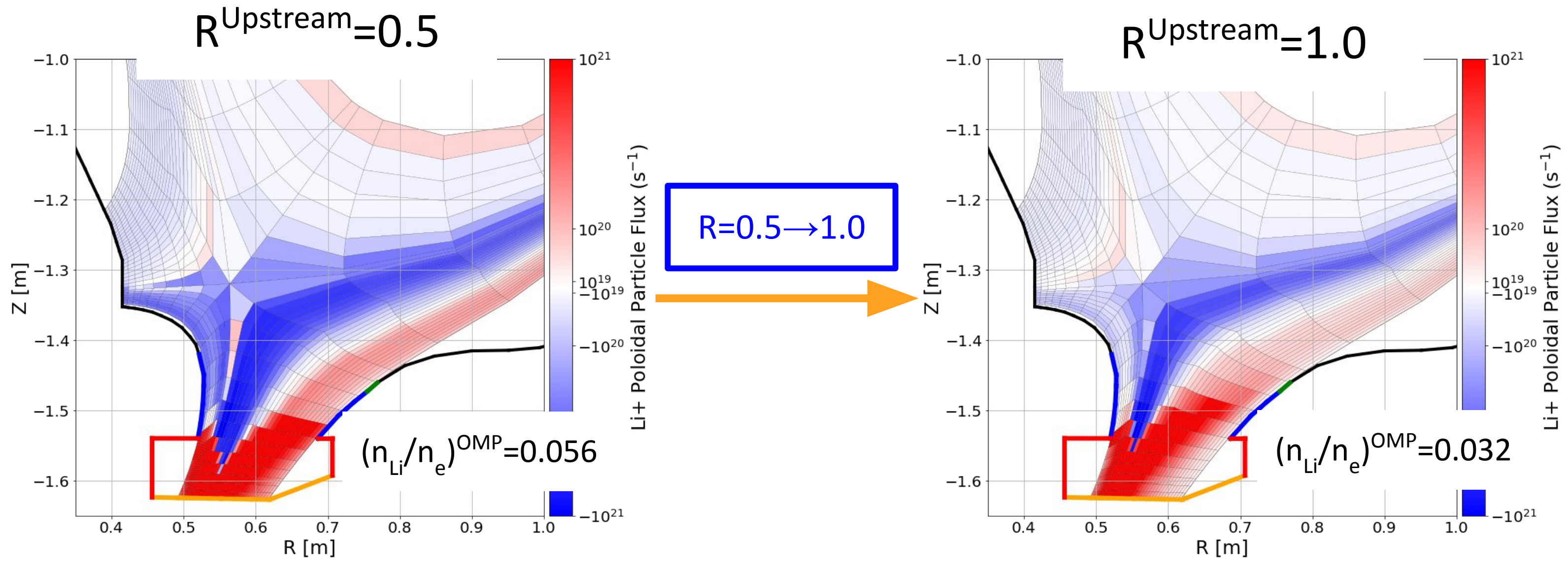
Changing Upstream Recycling

- Testing sensitivity to upstream recycling coefficient (blue walls)
- Pumping at walls above the box can be controlled via surface temperature and deuterium loading



Upstream Pumping Reduces Impact of Gas Puff

Downstream-directed Li Flow
Upstream-directed Li Flow

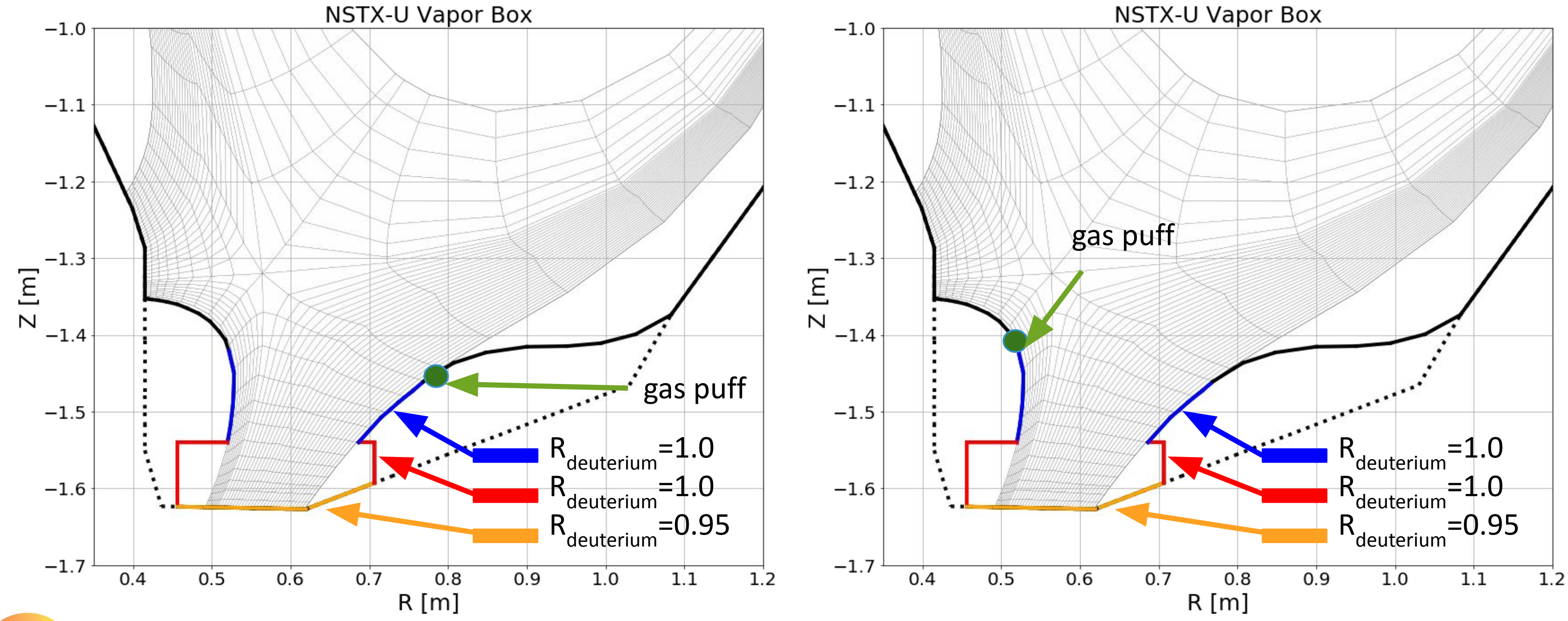


- Region of target-directed flow expands significantly with reduction of upstream pumping

Changing Transport Coefficients

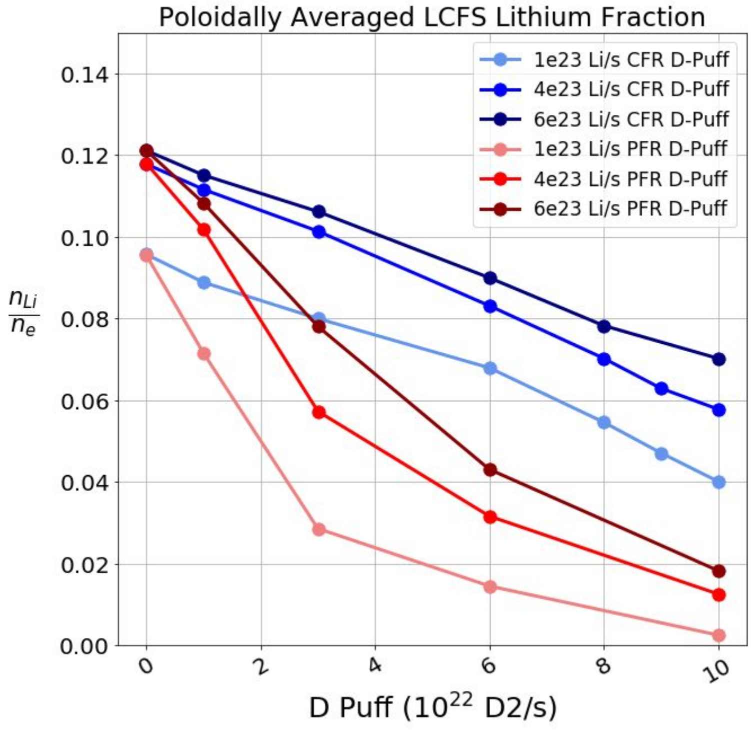
- Reduce D_n in core so that particle flux from core goes down
  - Γ^{core} = 9.0e22 D^+/s $\rightarrow$ 3.5×10^{22} D^+/s
- Reduce χ in SOL to have more conservative estimate for λ_q
  - Q_{tar}^{max} = 65 MW/m^2 $\rightarrow$ 92 MW/m^2 in base case
- λ_q = 4.8 mm $\rightarrow$ 2.8 mm
- R = 1.0 upstream

CFR vs PFR Puffing Location

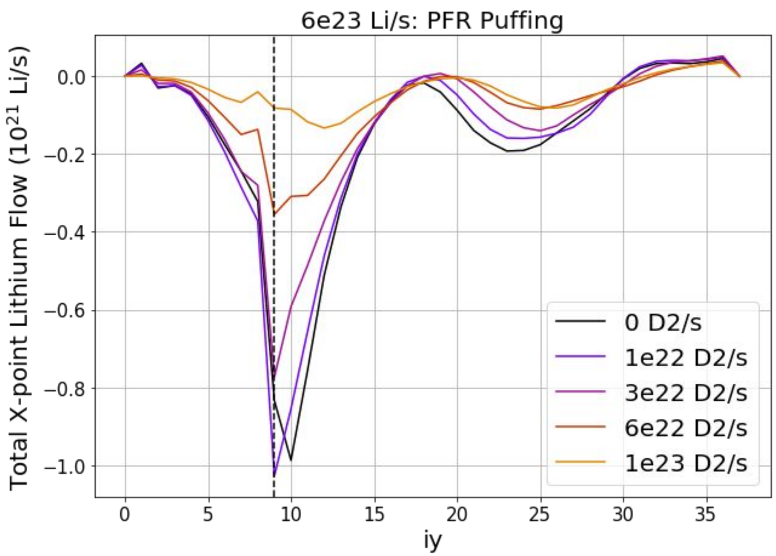


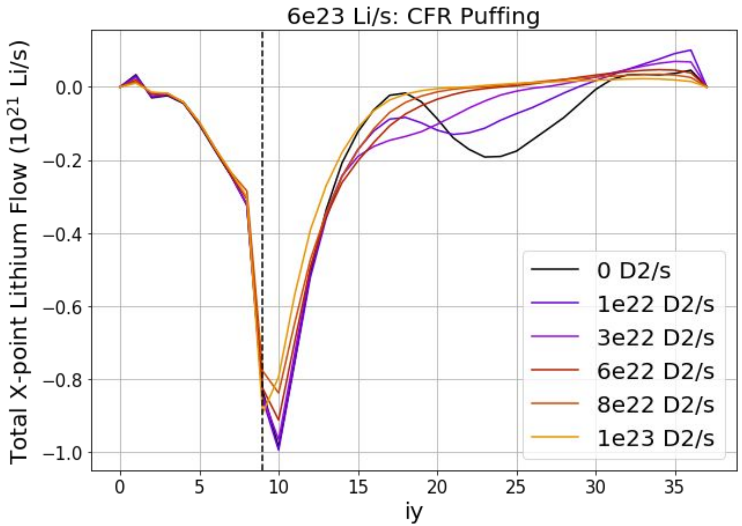
PFR puff is more effective at upstream lithium reduction

- PFR puffing is much more effective than CFR puffing at upstream lithium reduction
- Difference can be greater than a factor of three for most extreme cases



PFR Puff Is Effective at Limiting Upstream Directed Flow

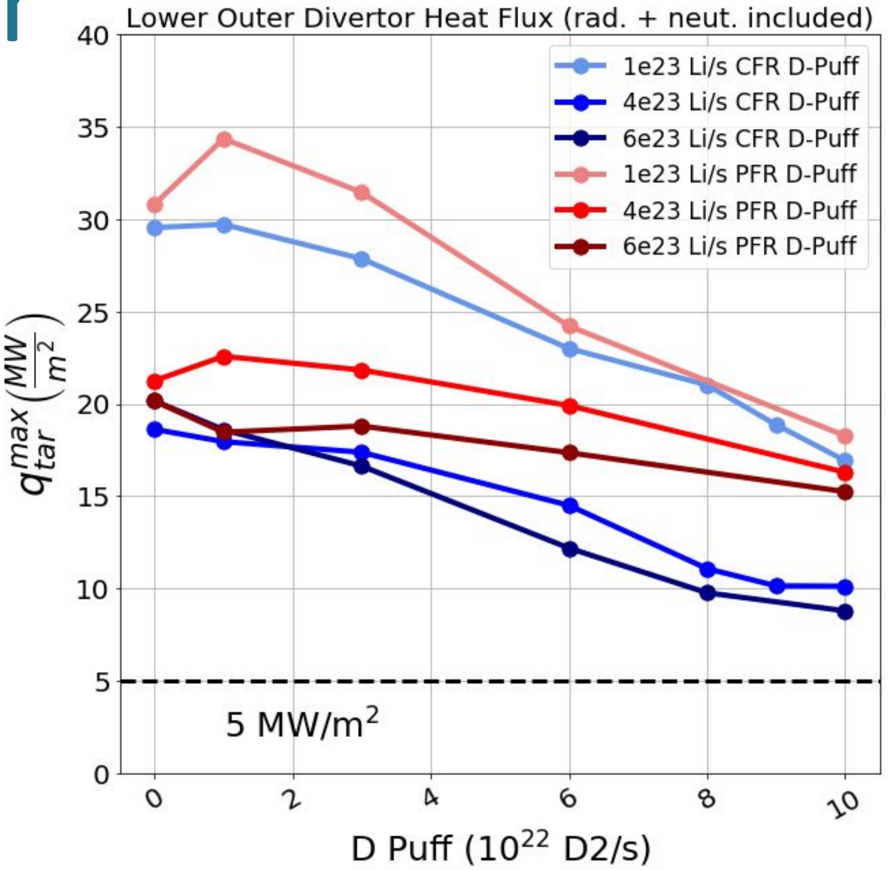




- Upstream-directed separatrix lithium flow is only reduced by PFR puffing (negative is upstream)

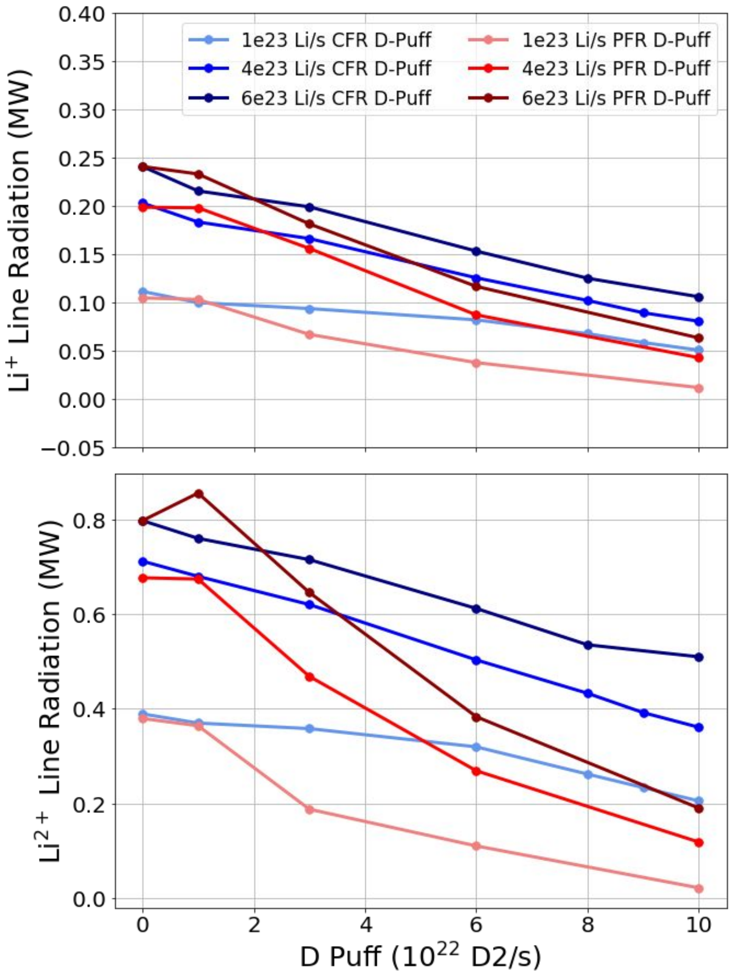
CFR Puff Has Lower Heat Flux

- For lithium and deuterium rates tested, PFR puffing was able to get to 15 MW/m^2 while CFR puffing was able to get below 10 MW/m^2
  - Starting from 92 MW/m^2



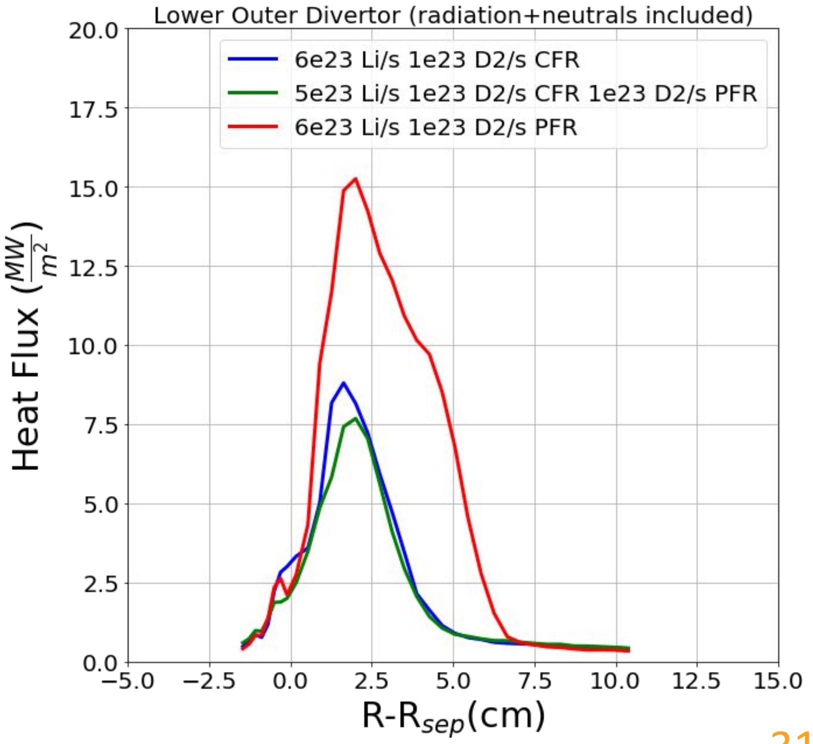
CFR Puff Has More Line Radiation

- Lithium line radiation is reduced more so by PFR puffing than CFR puffing
- Less lithium content in the plasma led to less lithium radiation



Simultaneous Puffing Leads to Low Heat Flux and Low Upstream Lithium

- Puffing from both sides can lead to the best of both worlds.
- $(n_{Li}/n_e)^{LCFS}$
  - PFR: 0.018
  - Both: 0.0049
  - CFR: 0.076
  - None: 0.12
- No OMP temperature reduction



Summary

- Detached solutions exist for current NSTX-U PFCs, but upstream ionization leads to non-negligible lithium content
- Baffles benefit neutral containment seen across a variety of powers; Engineering Trade-Offs T.B.D
- 65 MW/m^2 can be reduced to ~ 5 MW/m^2 with a lithium density ~ few percent of the upstream electron density

Summary

- Upstream deuterium pumping is seen to have detrimental effects on upstream lithium concentration due to reduction in fuel puff efficacy
- PFR puffing is more effective at upstream lithium reduction due to reduction of upstream-directed lithium flow at separatrix
- CFR puffing is more effective at cooling since the high lithium content upstream allows more Li^{2+} line radiation

Back-Up Slides

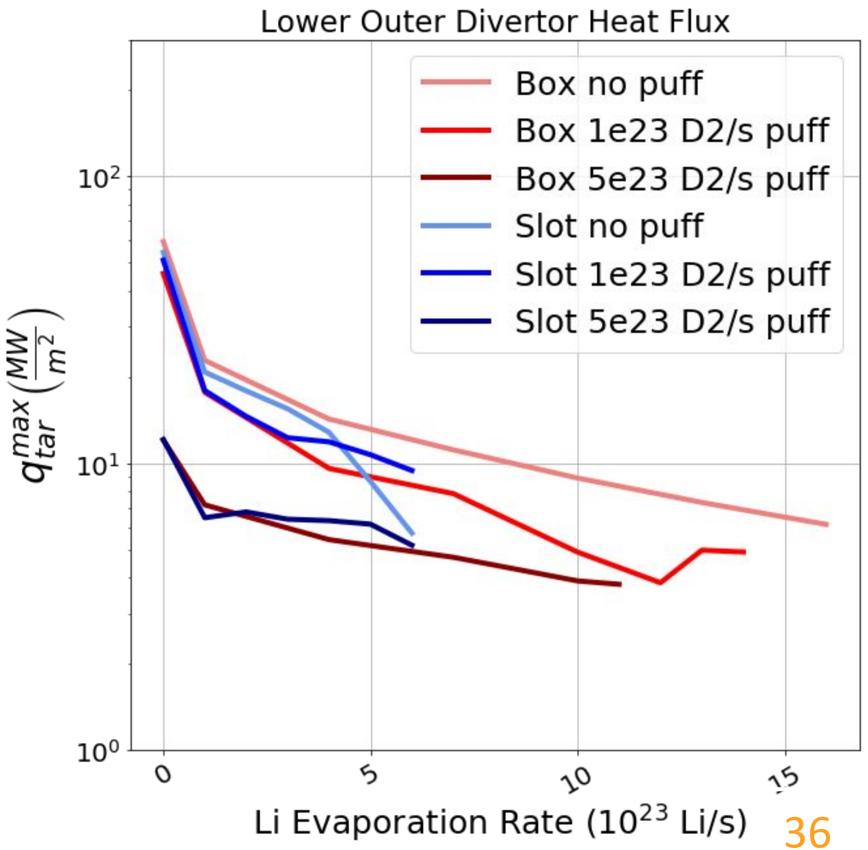
Future Work

- Near term
  - Sensitivity to target recycling coefficient
  - Sensitivity to target lithium evaporation
- Longer term
  - Further optimization
  - Include drifts in SOLPS simulations (HFS Target)
  - Integration with NSTX-U engineering

Divertor Heat Flux

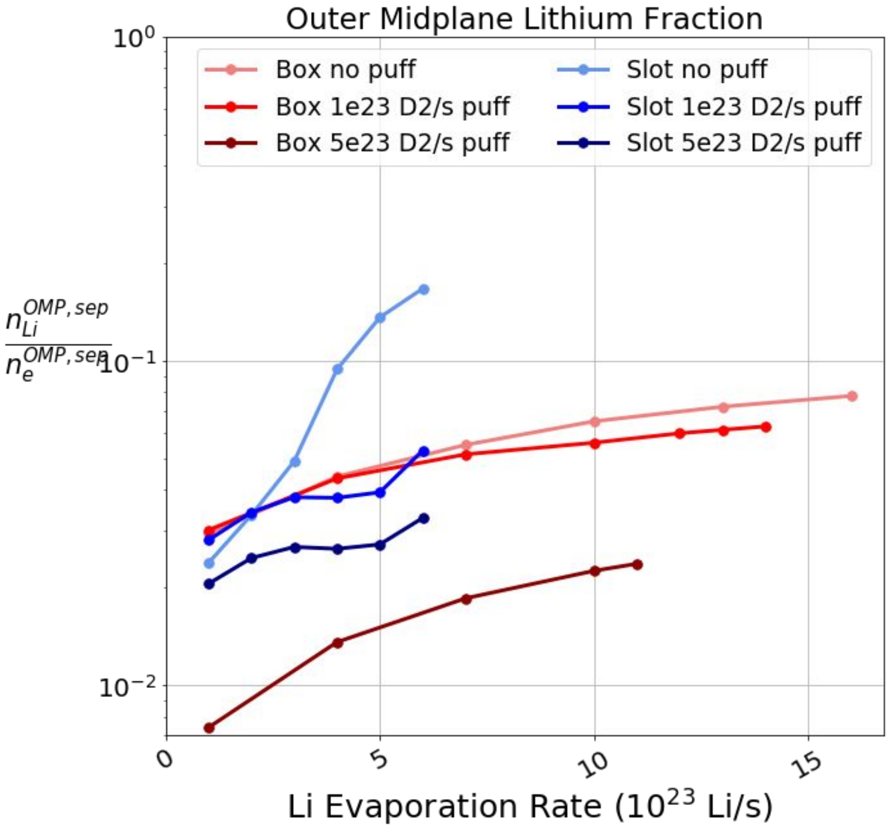
- Slot has difficulty getting below 5 MW/m^2 even at highest deuterium puffing rate tested
  - Slot goes unstable beyond 6 x 10^{23} Li/s
- Box can contain the lithium and reduce heat to the target

Radiation + neutral heat included



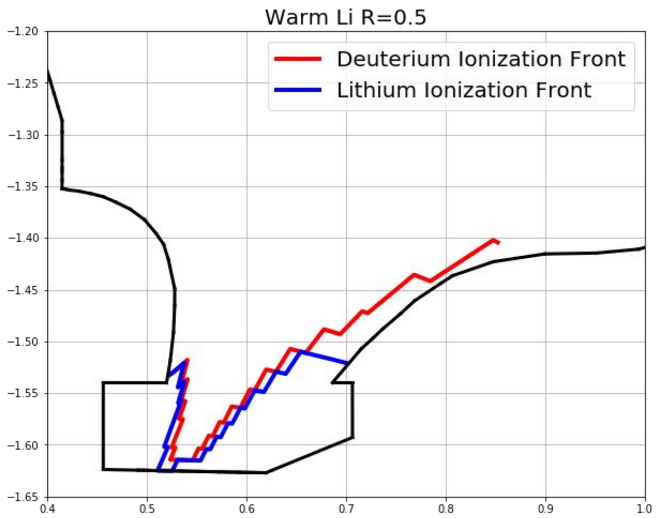
Lithium Fraction

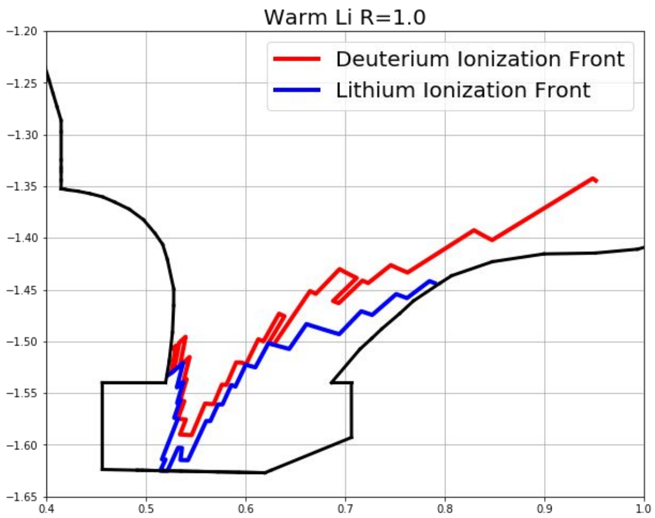
- Upstream lithium content in the slot geometry is less controlled
- The baffles are important for lithium containment



Ionization Front Comparison

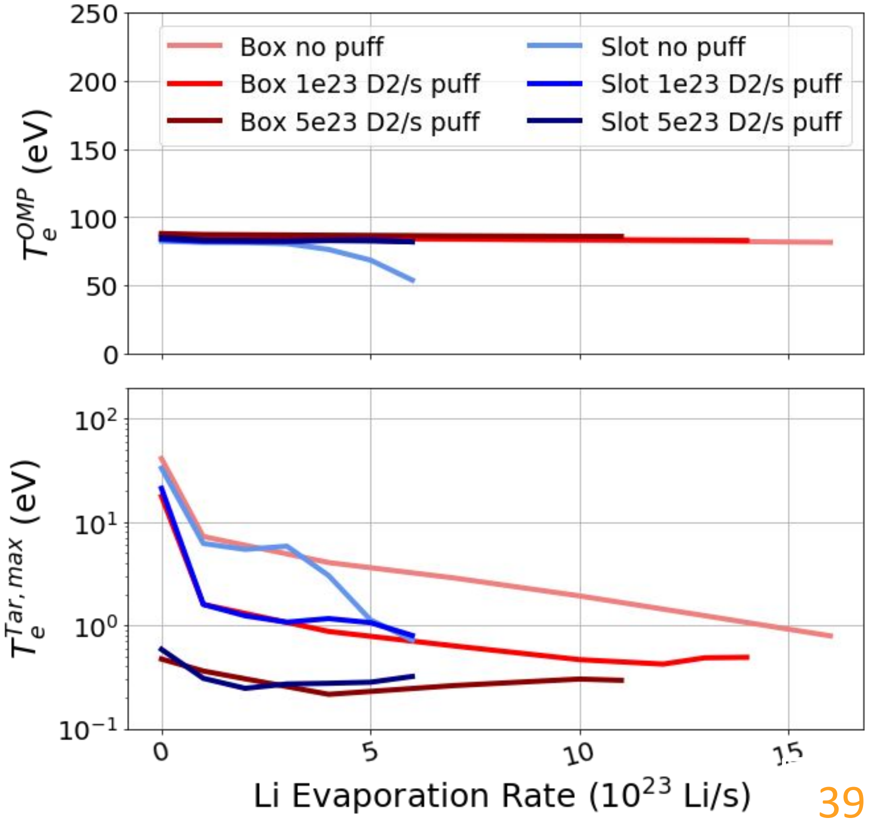
- Comparing ionization front between lithium and deuterium shows R^D_{warm}=1.0 makes deuterium ionization front above lithium, which is good for impurity containment (Casali et al. 2020)



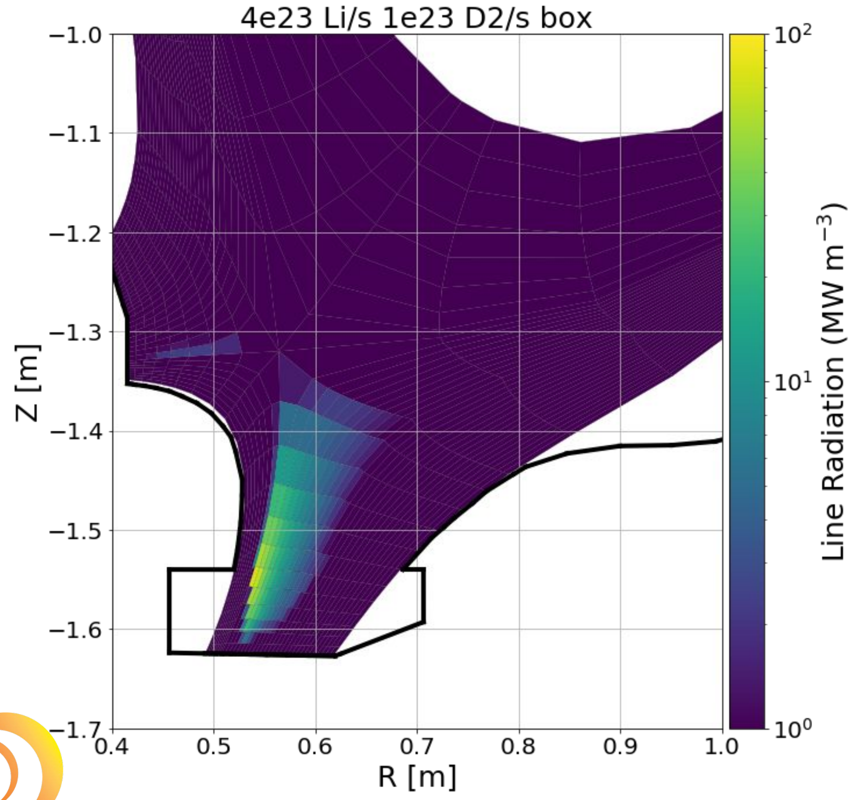


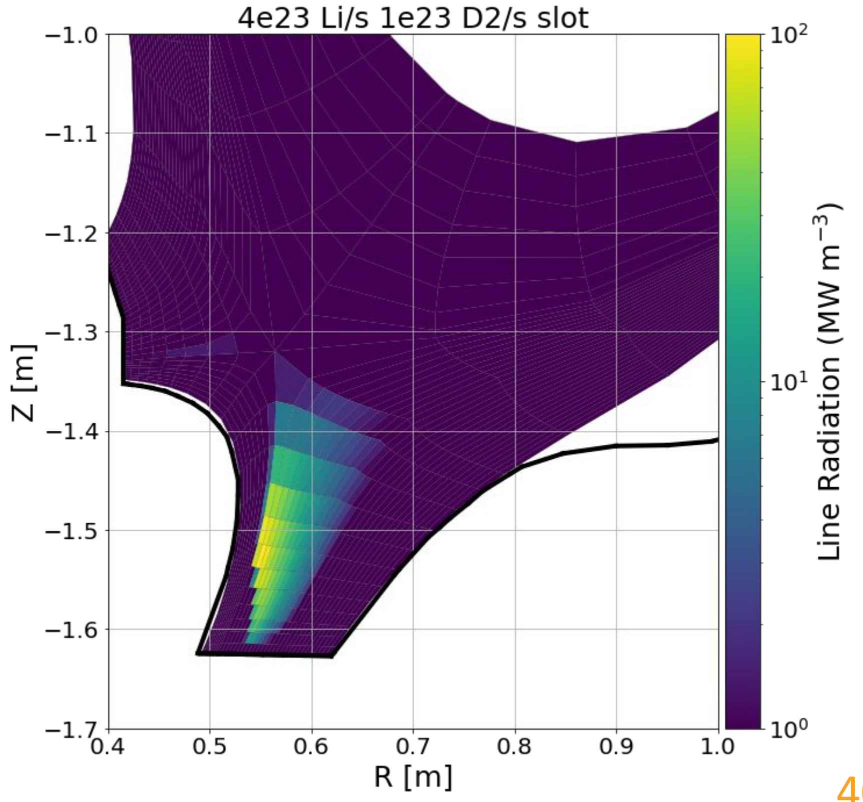
Effects on Temperature

- The upstream temperature is mostly unaffected by the increase in lithium evaporation
  - Divertor closure does well at isolating cooling from upstream plasma
- Slot performs similarly to box at high puffing but at no puffing the slot sees upstream temperature degradation as lithium evaporation is increased



2D Line Radiation





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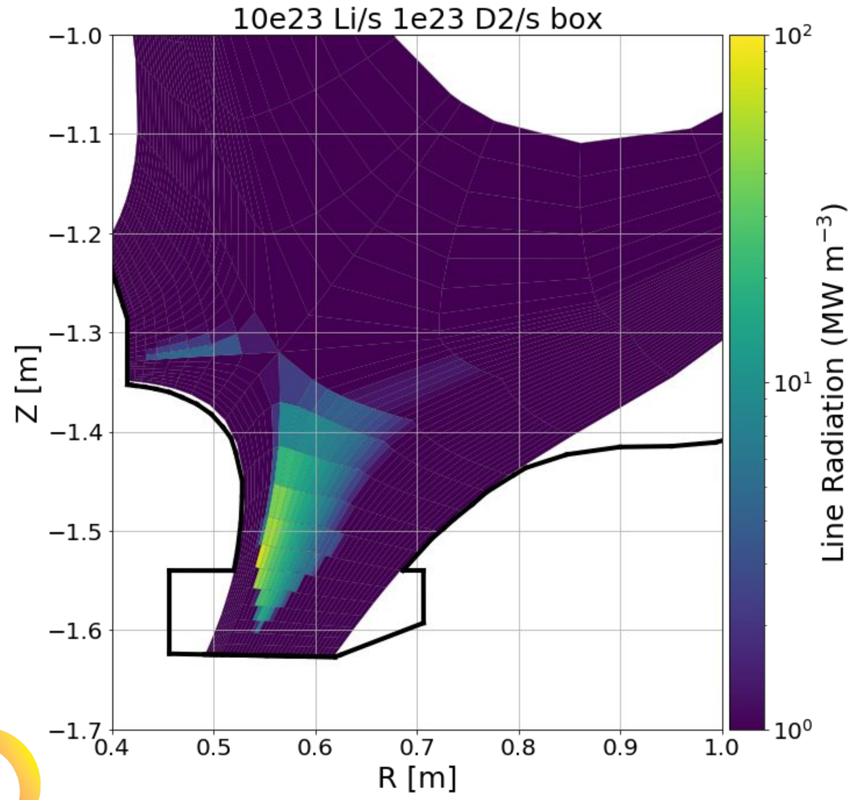
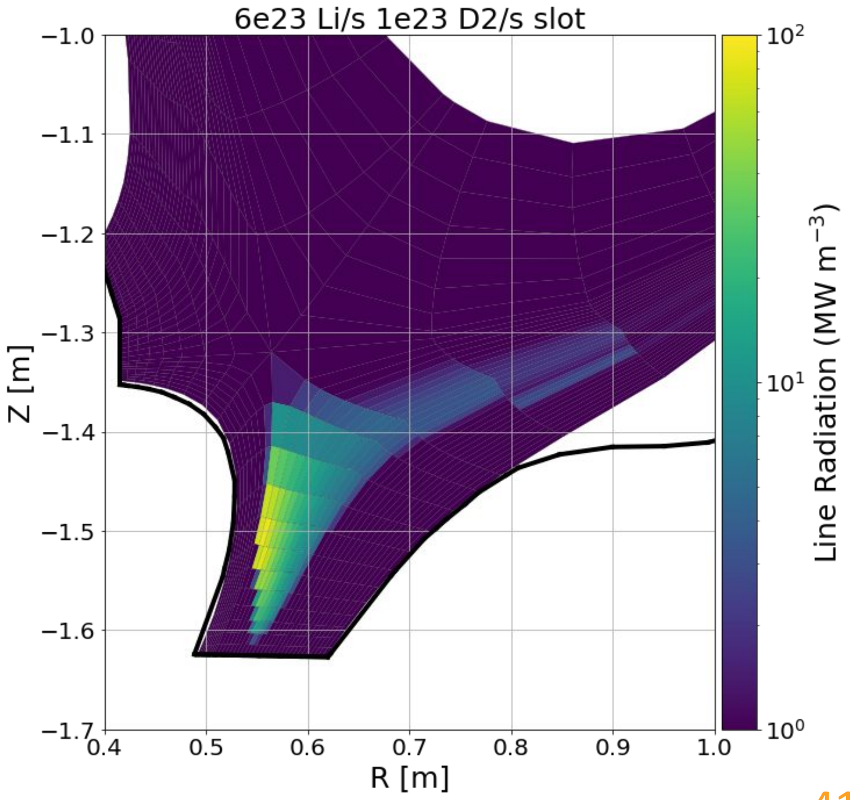
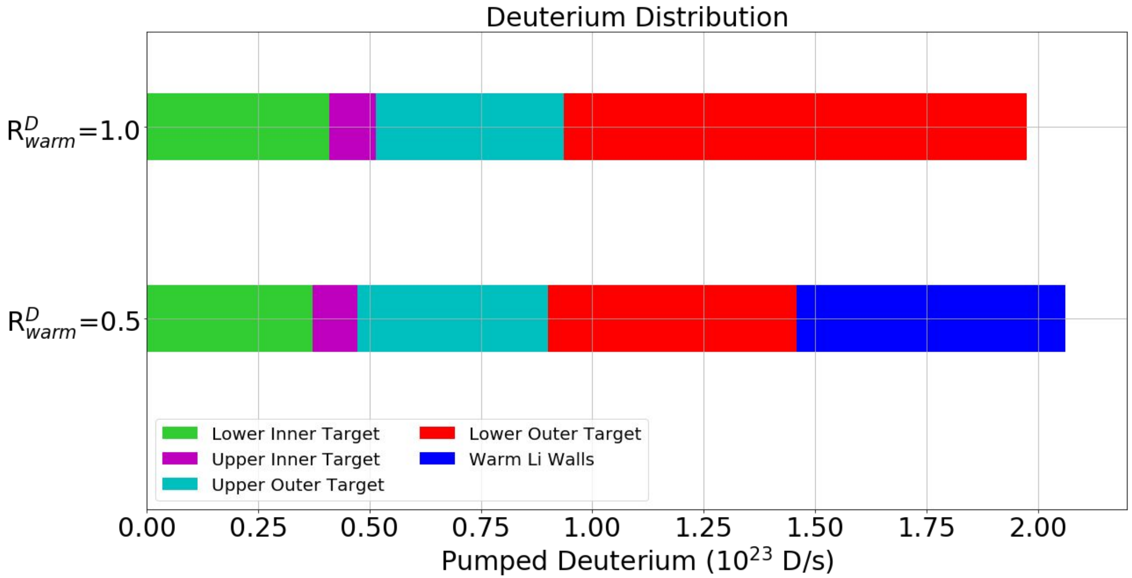




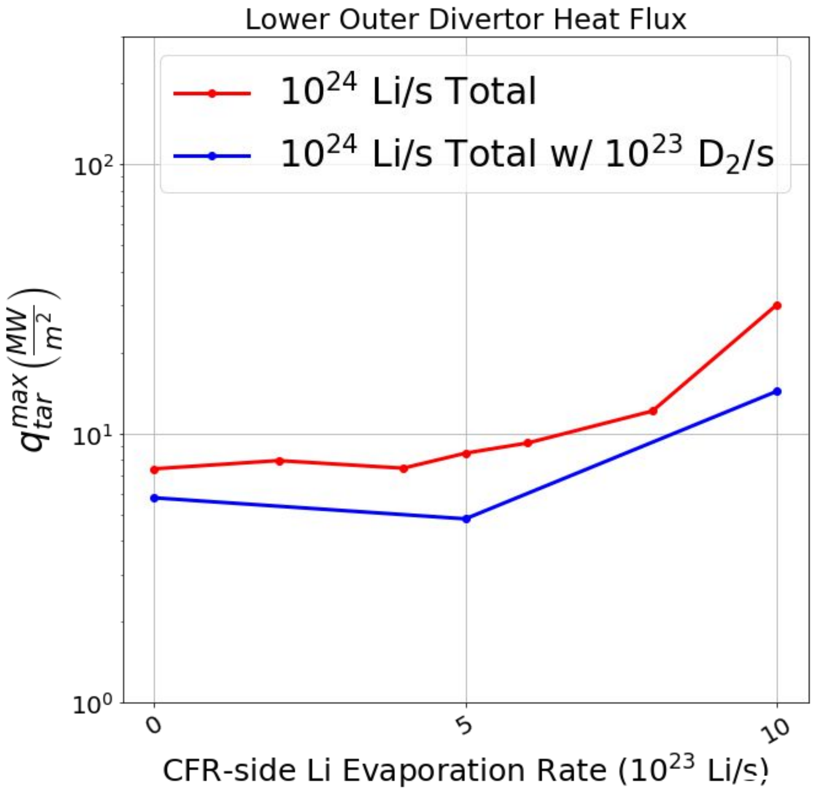
Pumping At Warm Liquid Li Walls Reduces Impact of Gas Puff

- Pumping at upstream walls removes puffed deuterium before it can be ionized and cause higher recycling rates, which stabilizes lithium fraction



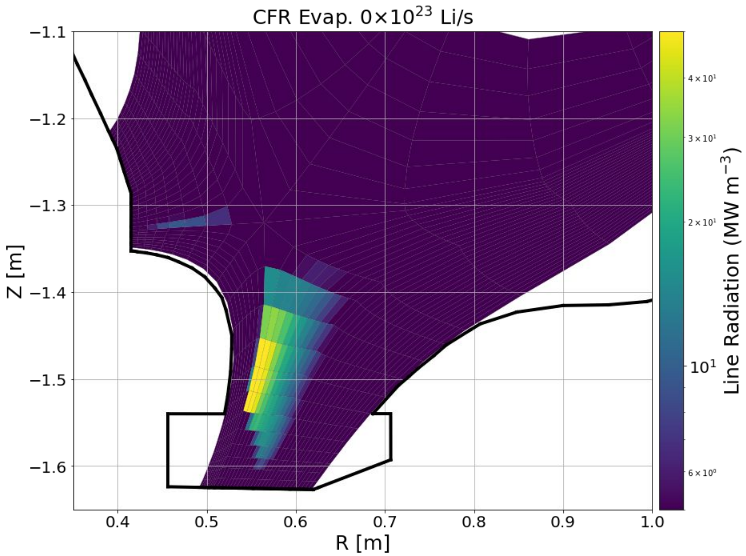
PFR Evaporation More Effective than CFR

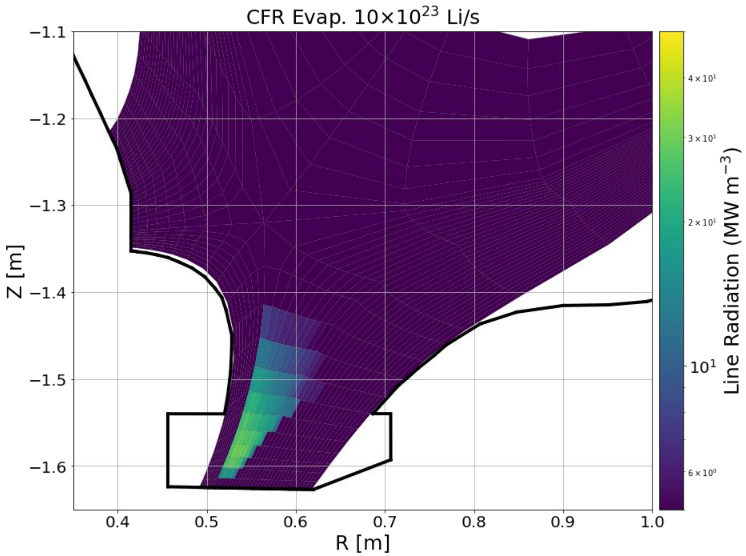
- Attempting to have imbalanced evaporation has shows little difference between entirely PFR evaporation and a balanced scenario
- Entirely CFR side evaporation is significantly less efficient
- May simplify system



Asymmetric Evaporation

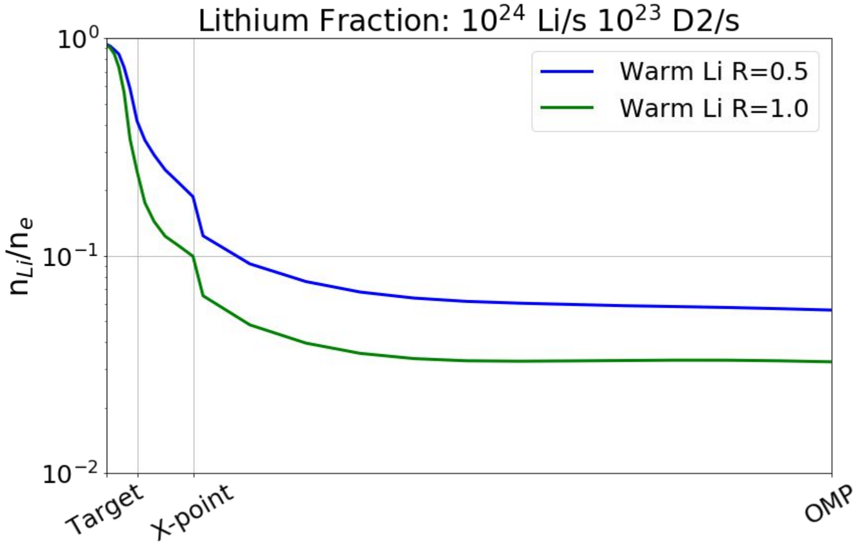
- Access to high density separatrix field line makes PFR lithium evaporation radiate more easily





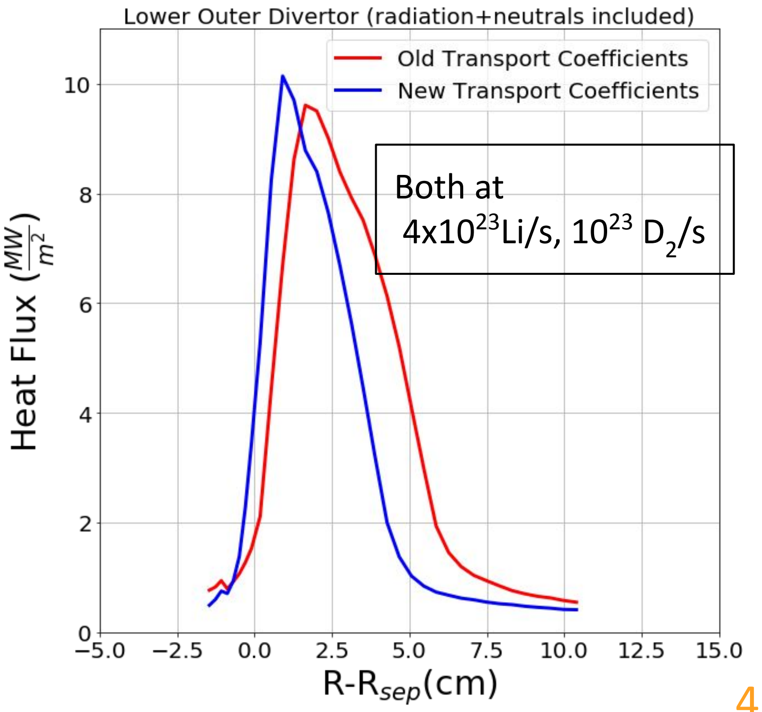
Upstream Recycling Decreases Lithium Fraction

- Lithium reduced throughout SOL by reducing pumping
- Reducing deuterium pumping helps reduce lithium fraction
  - $(n_{Li}/n_e)^{OMP,sep}$=0.056⟶0.032



Transport Coefficients Not Significant for Heat Flux

- Despite raising heat flux from 65 MW/m^2 to 92 MW/m^2 in the base case, the heat flux after evaporating lithium was not sensitive to change in transport coefficients



Transport Coefficients Are Significant for Upstream Lithium

- At 4×10^{23} Li/s and 10^{23} D_2/s
  - Old Transport Coefficients: $(n_{Li}/n_e)^{OMP} = 0.044$
  - New Transport Coefficients: $(n_{Li}/n_e)^{OMP} = 0.065$
- Particle flux from core is an important parameter for lithium containment!