A Lithium Vapor Divertor For NSTX-U : Physics Motivation

Presenter: Eric Emdee

Co-authors: Robert Goldston ; Rajesh Maingi ; Andrei Khodak ; Matt Parsons ; Margaret Porcelli

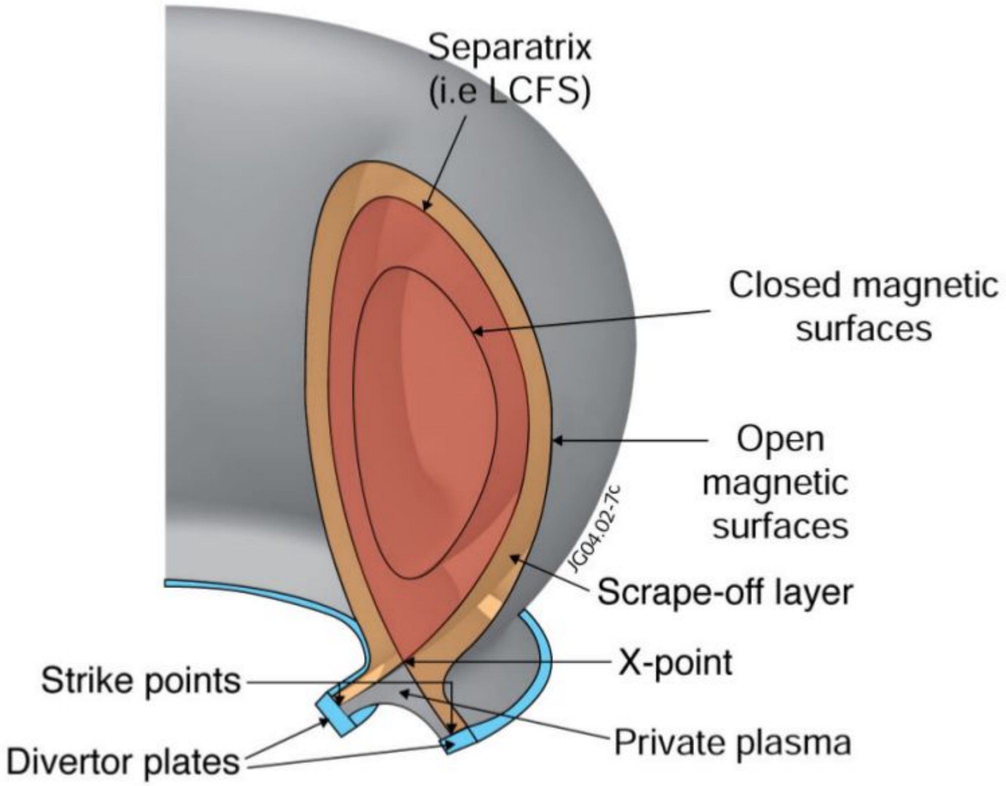
May 5th, 2025

NSTX-U Monday Meeting

Introduction: Fusion Reactors Face High Heat Fluxes At Target

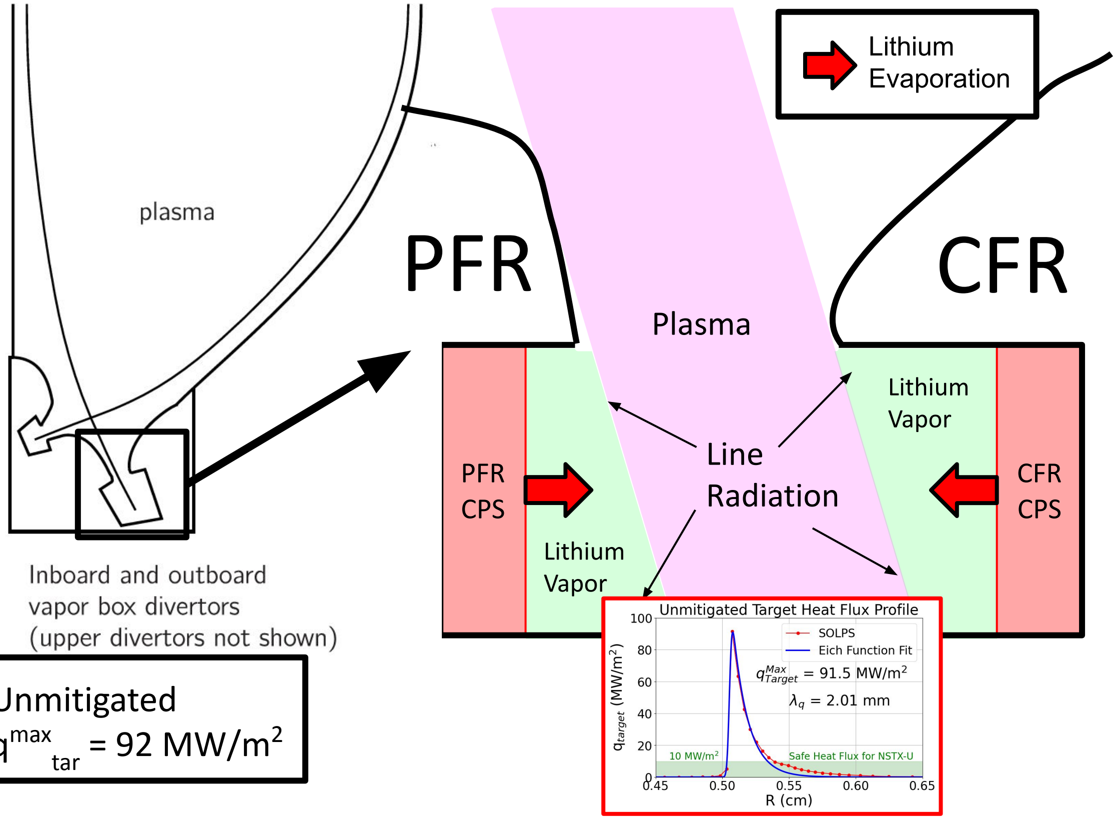
- Divertors concentrate the energy from the plasma into a small area leading to high surface heat fluxes

- Dissipating the plasma power before interacting with the divertor plates, known as **detachment**, will be necessary in future fusion reactors
  - NSTX-U is an optimal test bed for detached scenarios, since high target heat fluxes via high flux compression are achievable



The Lithium Vapor Box Divertor

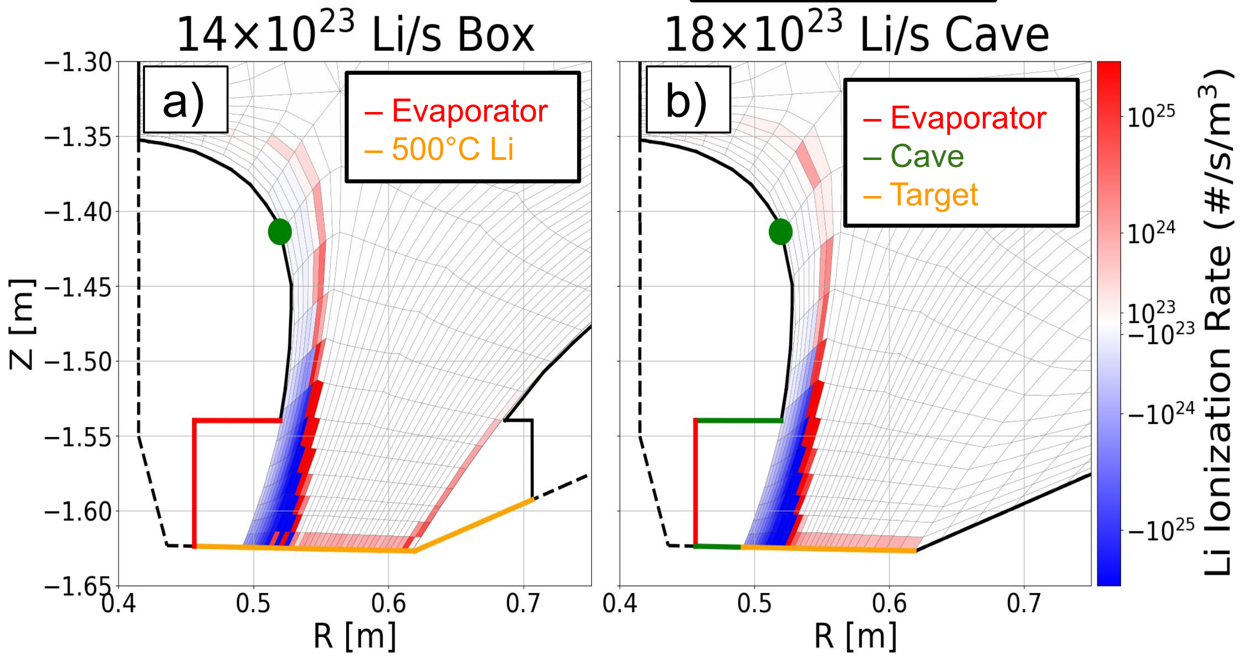
- Detachment via lithium evaporation
- In this presentation I am demonstrating the result of different PFC designs
- Trying to minimize $(n_{Li}/n_e)^{LCFS}$ while reducing target heat flux to <10MW/m^2 with SOLPS modeling



Low Lithium Concentration Maintained Without Common Flux Region Baffles

- The CFR baffling was removed to make a vapor *cave*
- The vapor cave can reach q^{max}_{tar}<10MW/m^2 with $(n_{Li}/n_e)^{LCFS}$=0.041 while the vapor box can do the same with $(n_{Li}/n_e)^{LCFS}$=0.038

10^{23} Li/s ~ 1 g/s !



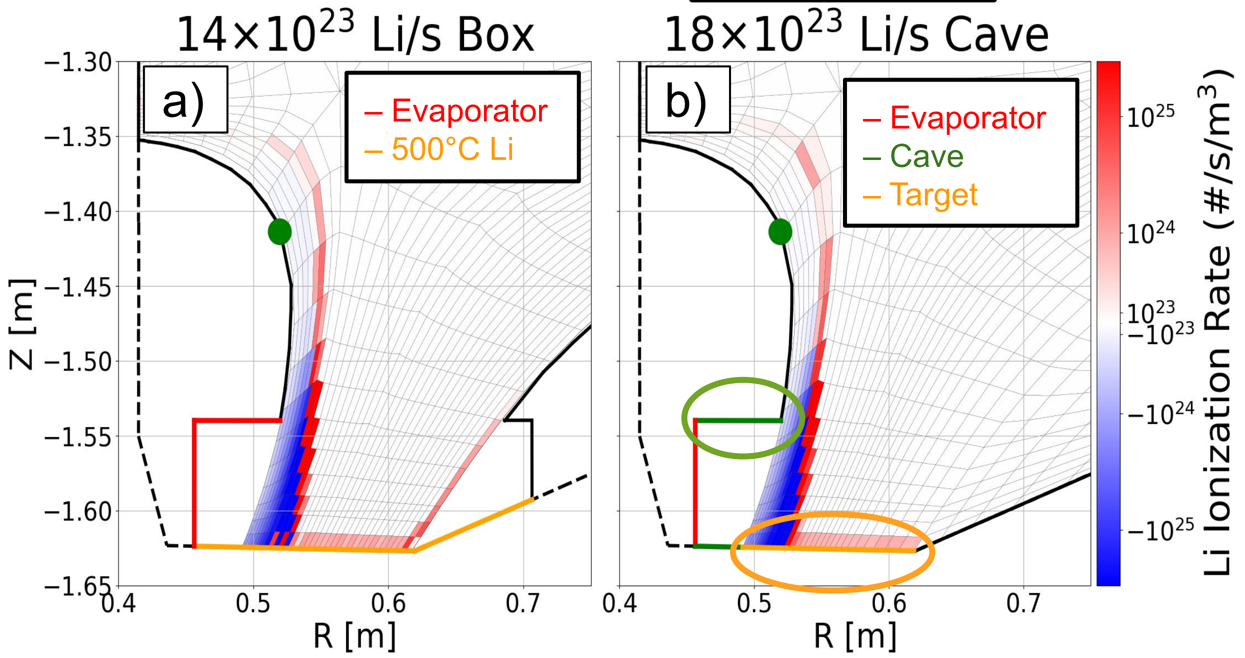
E.D Emdee et al. Nuclear Fusion 64 (2024) 086047

Low Lithium Concentration Maintained Without Common Flux Region Baffles

- The CFR baffling was removed to make a vapor *cave*

- The vapor cave can reach q^{max}_{tar}<10MW/m^2 with $(n_{Li}/n_e)^{LCFS}$=0.041 while the vapor box can do the same with $(n_{Li}/n_e)^{LCFS}$=0.038

10^{23} Li/s ~ 1 g/s !

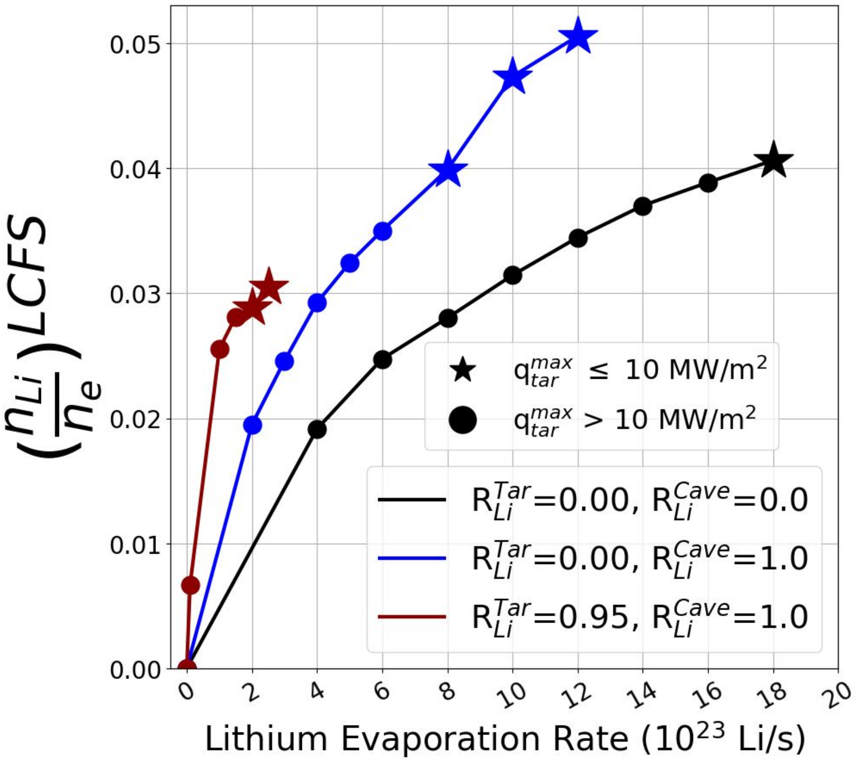


E.D Emdee et al. Nuclear Fusion 64 (2024) 086047

Lithium Emission and Upstream Concentration Improved With Reflecting Li Surfaces

- Reflection of lithium at PFCs will occur when at high temperature

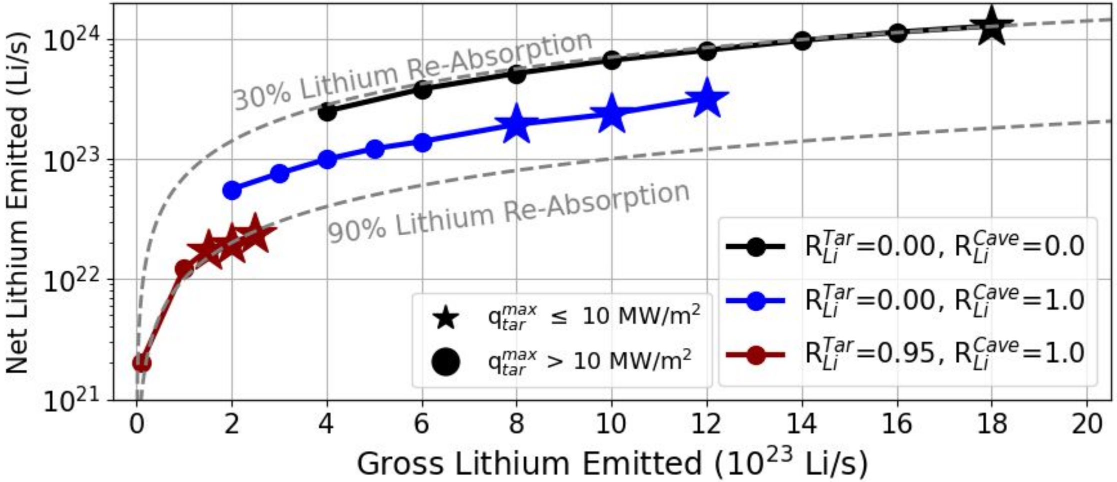
- Reflection at the target and cave walls leads to lower required upstream concentration $(n_{Li}/n_e)^{LCFS}$



E.D Emdee et al. Nuclear Fusion 64 (2024) 086047

Net lithium emission can be reduced to 230 mg/s

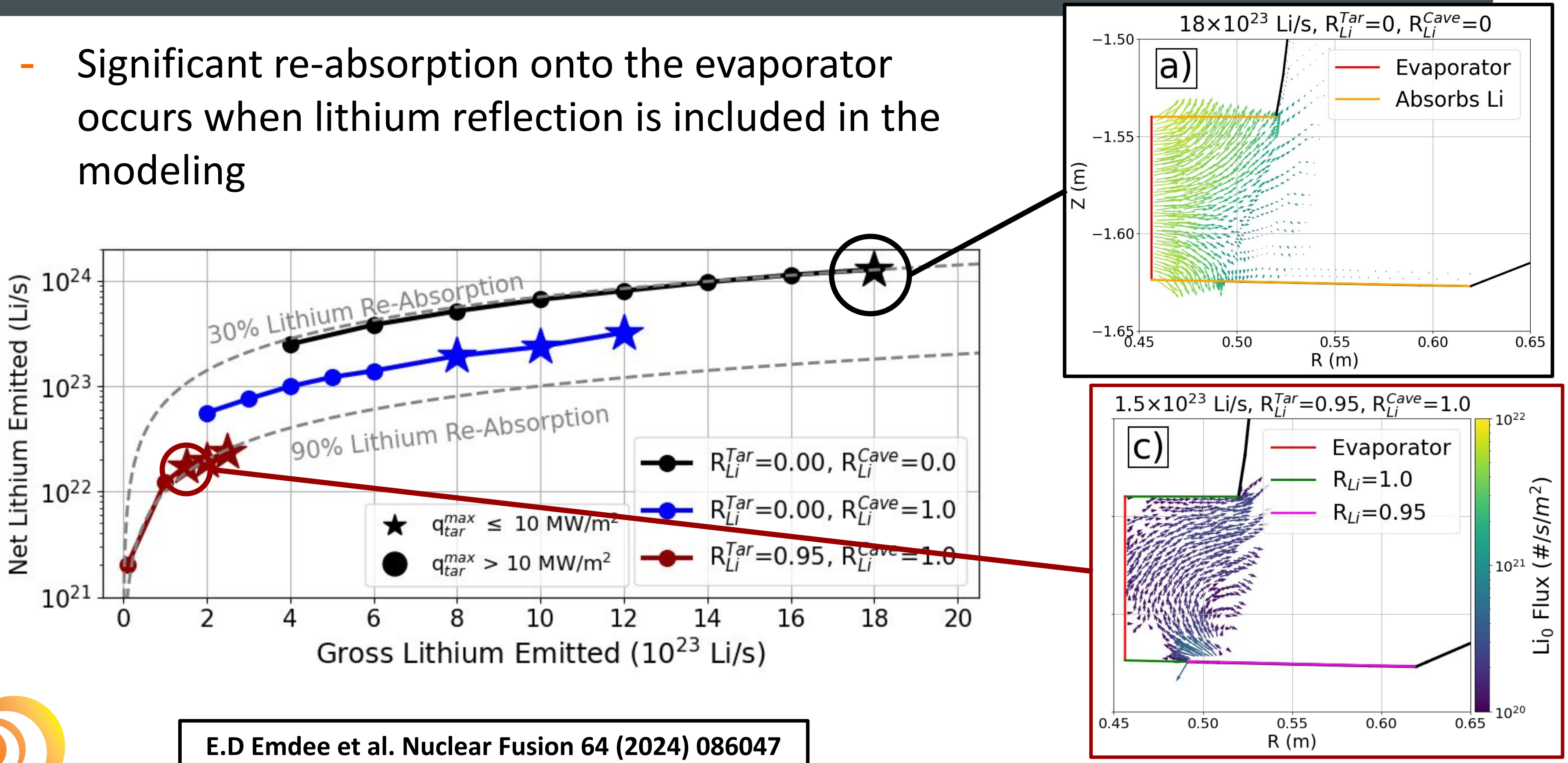
- Significant re-absorption onto the evaporator occurs when lithium reflection is included in the modeling



E.D Emdee et al. Nuclear Fusion 64 (2024) 086047

Net lithium emission can be reduced to 230 mg/s

- Significant re-absorption onto the evaporator occurs when lithium reflection is included in the modeling



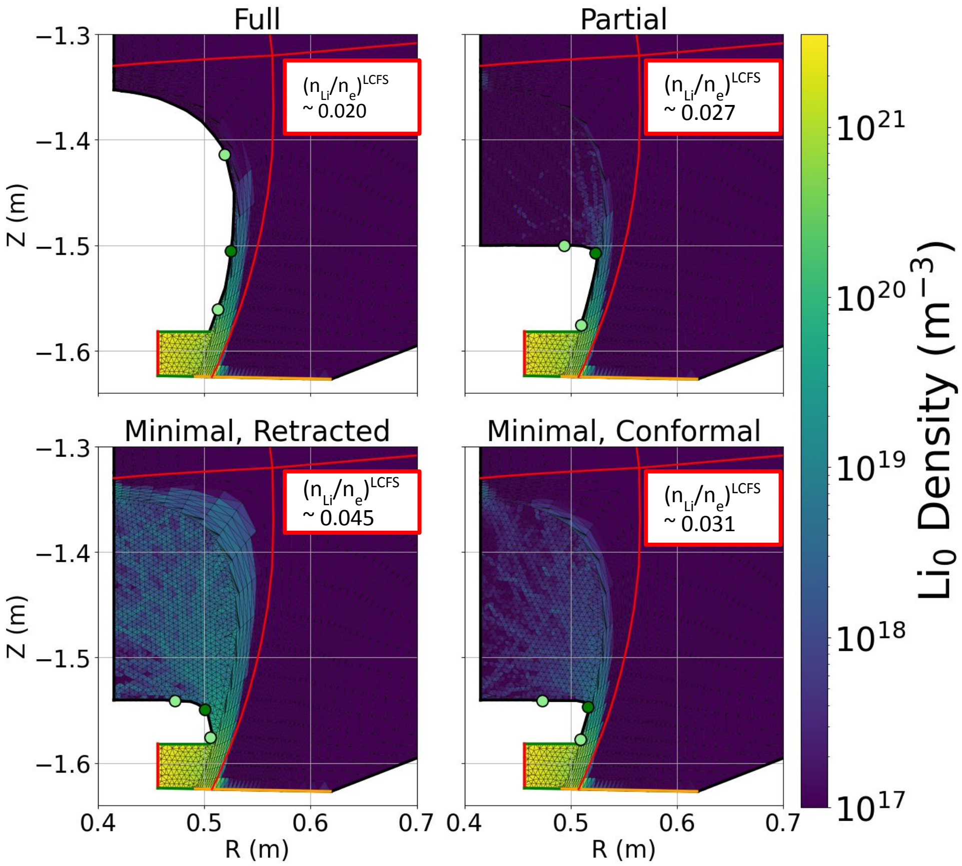
E.D Emdee et al. Nuclear Fusion 64 (2024) 086047

PFR Structure Affects Concentration Predictions

- Reductions in PFR structure see increased neutral lithium leakage

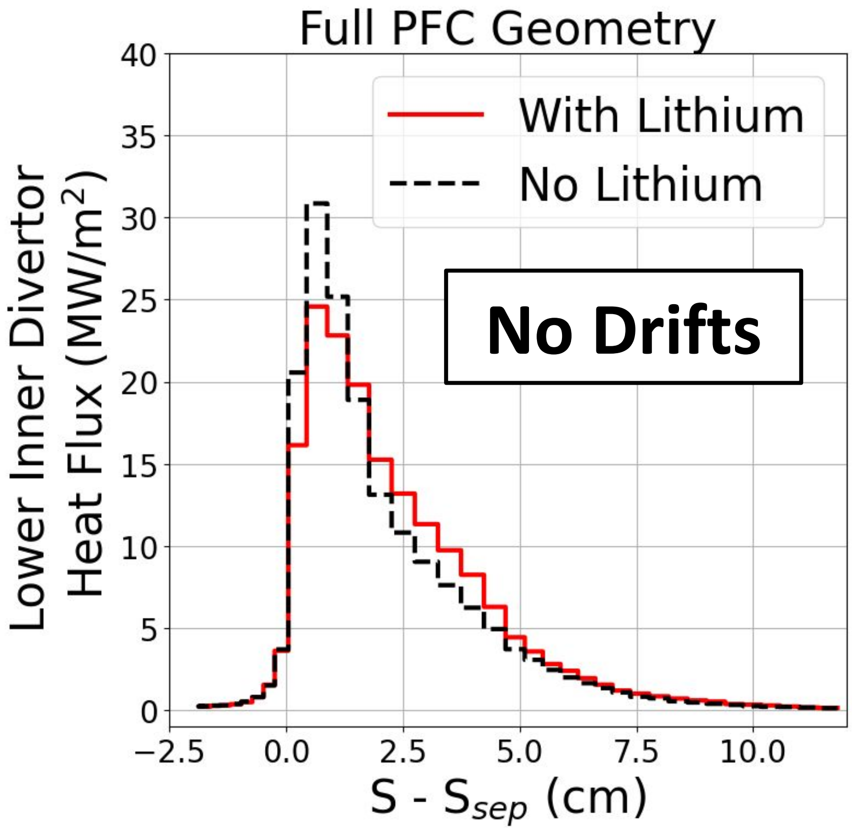
- If the PFR structure is conformal with the magnetic field line geometry, some lithium containment is recovered

E.D Emdee et al. Nuclear Materials and Energy 46 (2024) 101737



The Outer Divertor is Protected, but What About the Inner Divertor?

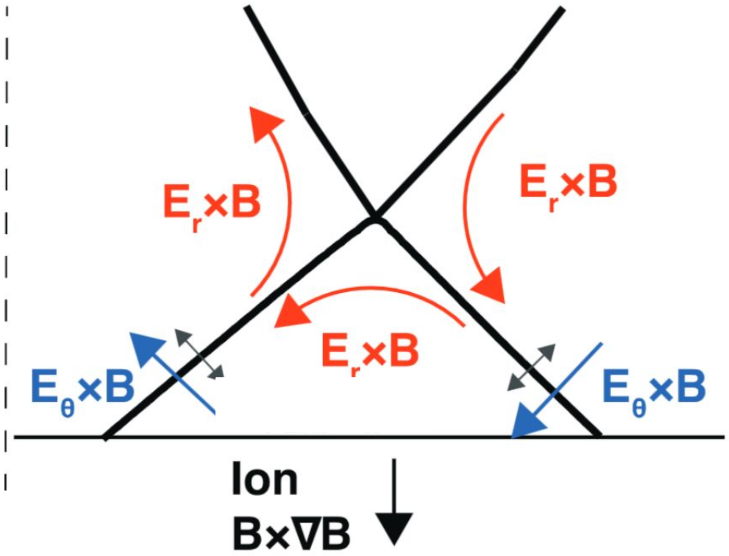
- The inner divertor is also facing a large heat flux, but is not very affected by the outer divertor lithium injection
- Drifts, not included in the modeling thus far, move lithium from the outer divertor, where it is injected, to the inner divertor via the Private Flux Region



Adding Drifts to SOLPS-ITER

- Drifts (E x B, B x ∇B) were not in SOLPS modeling due to significantly increased computation times
  - Took ~1-1.5 months per simulation
  - Speed-up work will hopefully yield faster turnaround times in the future, making this type of analysis more feasible

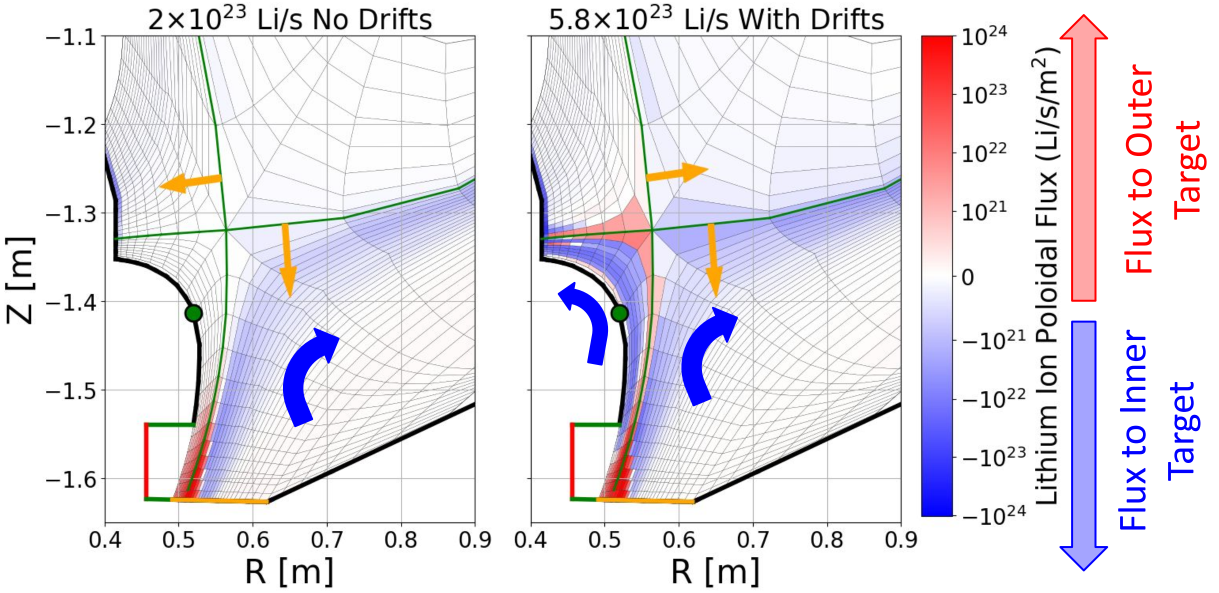
- We have explored the effect of drifts on design predictions for a limited set of cases



A.E. Jaervinen et al. Nuclear Materials and Energy 12 (2017) 1136–1140

Li Flow Depend on Drifts

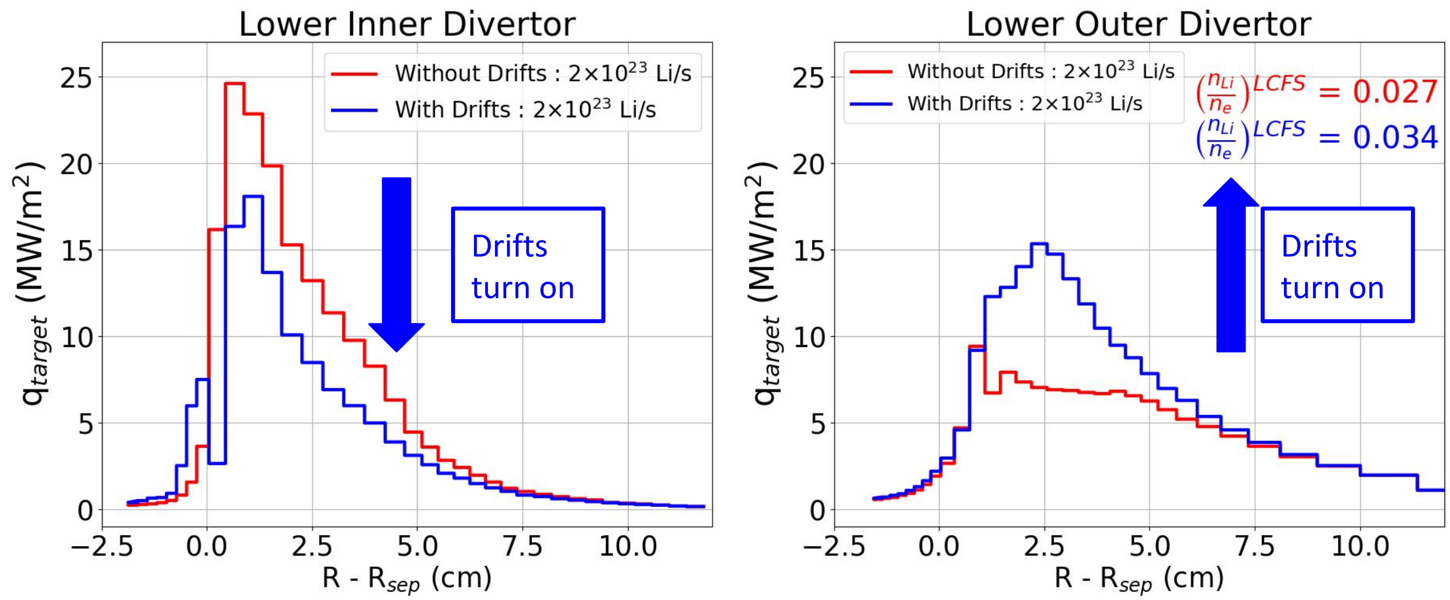
- When drifts are turned on, flow of lithium towards the inner target is observed
  - Similar to other observation of drifts in SOLPS



E.D Emdee et al. Nuclear Materials and Energy 46 (2024) 101737

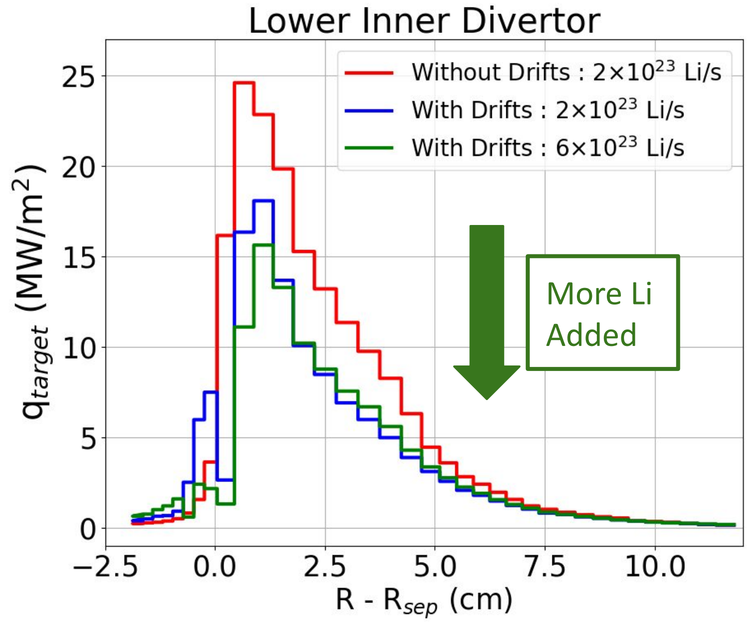
Drifts Decrease Heat Flux at the Inner Divertor, but Increase Heat Flux at the Outer Divertor

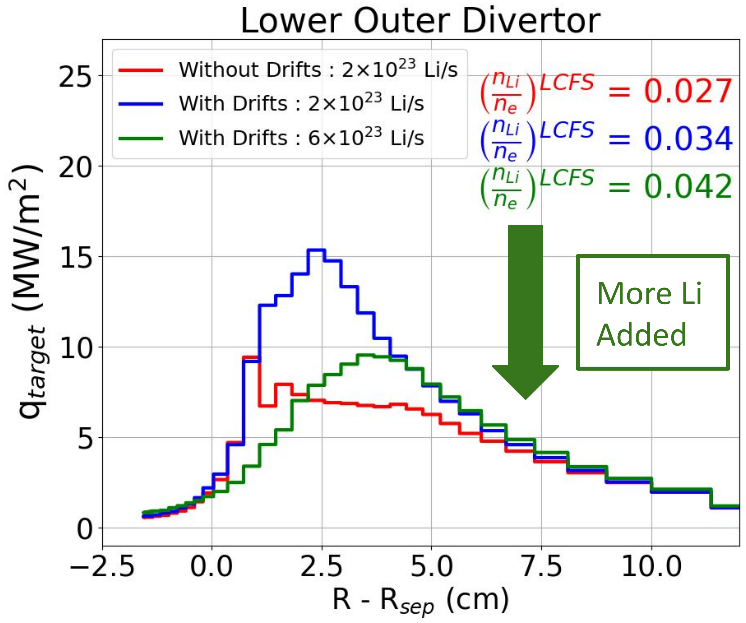
- Raises the prediction for required lithium concentration
  - Larger presence of lithium on the HFS due to altered impurity transport from drifts



We Can Detach the Outer Divertor Again With More Lithium

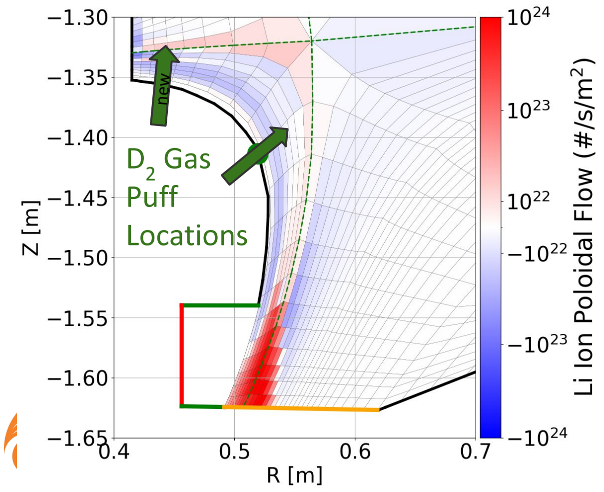
- Adding more lithium to detach the outer divertor also reduces the inner divertor heat flux

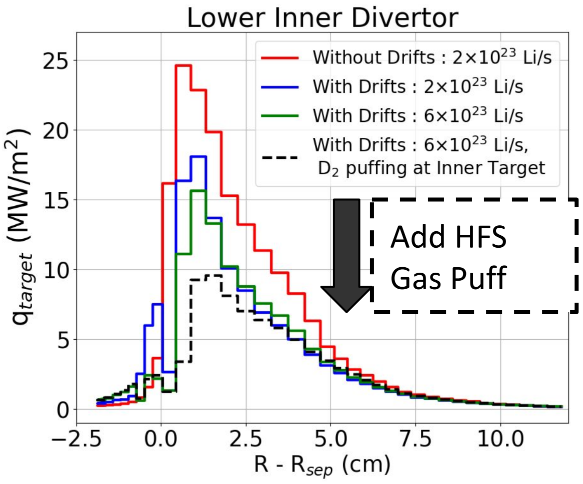


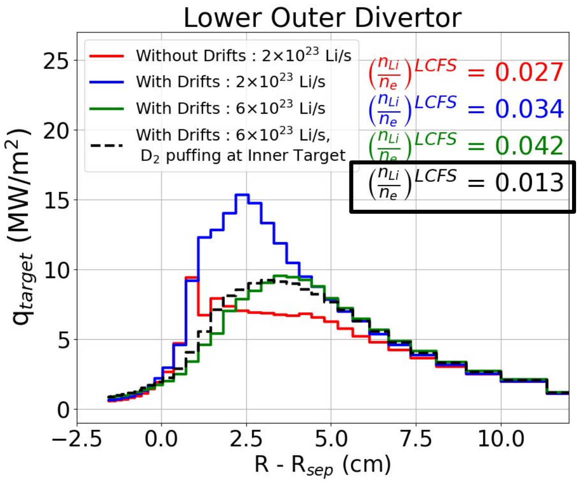


Adding D_2 Gas Puffing to the Inner Target May Be Necessary to Ensure PFC Safety

- Adding a gas puff near the inner divertor helps reduce the heat flux further, achieving a good solution for both divertors at 0.01-0.02 concentration

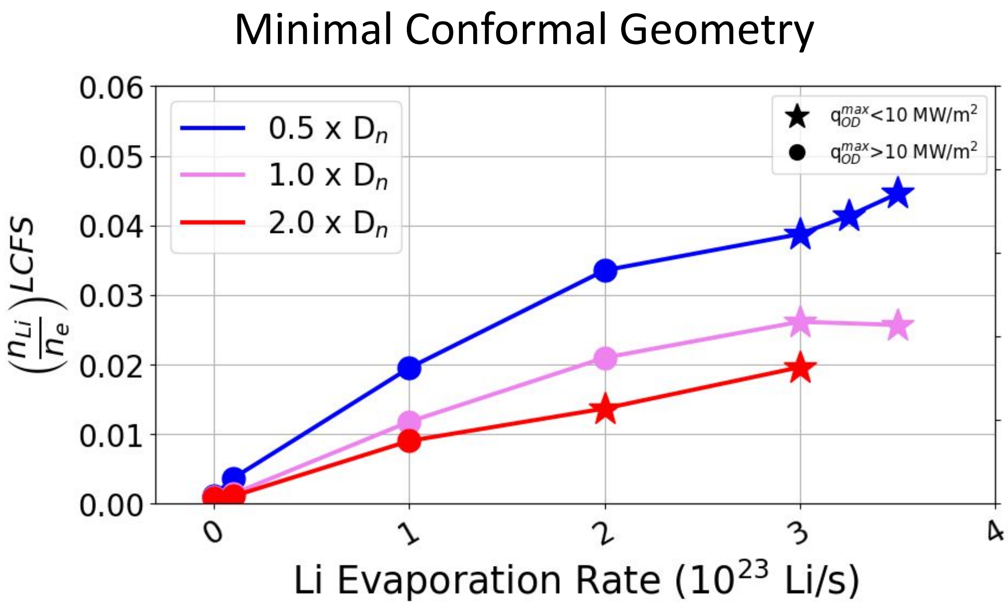






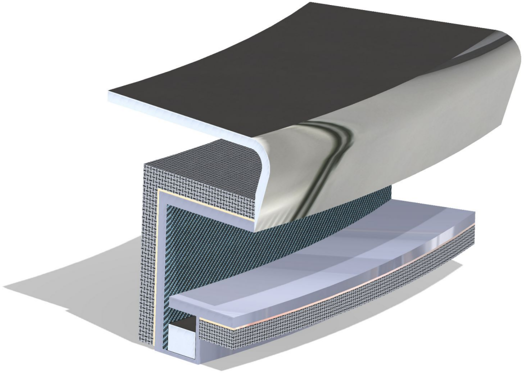
On-Going Work : Quantifying Uncertainties From Diffusive Transport Coefficients

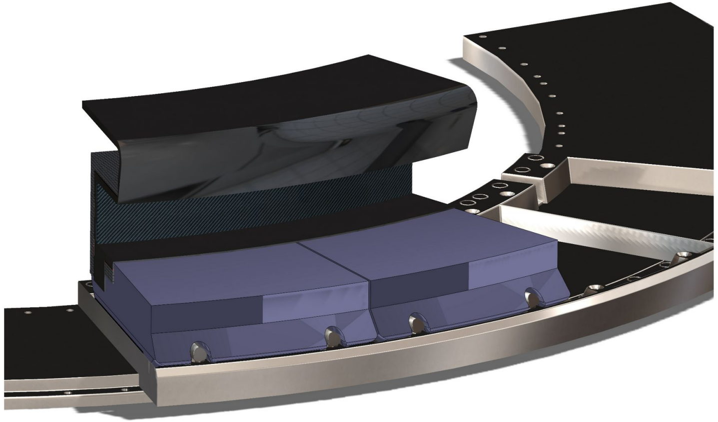
- Different particle and heat diffusivities, a user-defined quantity in SOLPS, can yield different predictions for:
  - Lithium injection rate
  - Upstream concentration
  - Gas puffing needed to control the concentration (and upstream density)
- Requires keeping flux of deuterium from the core constant for apples-to-apples comparison



Conclusions

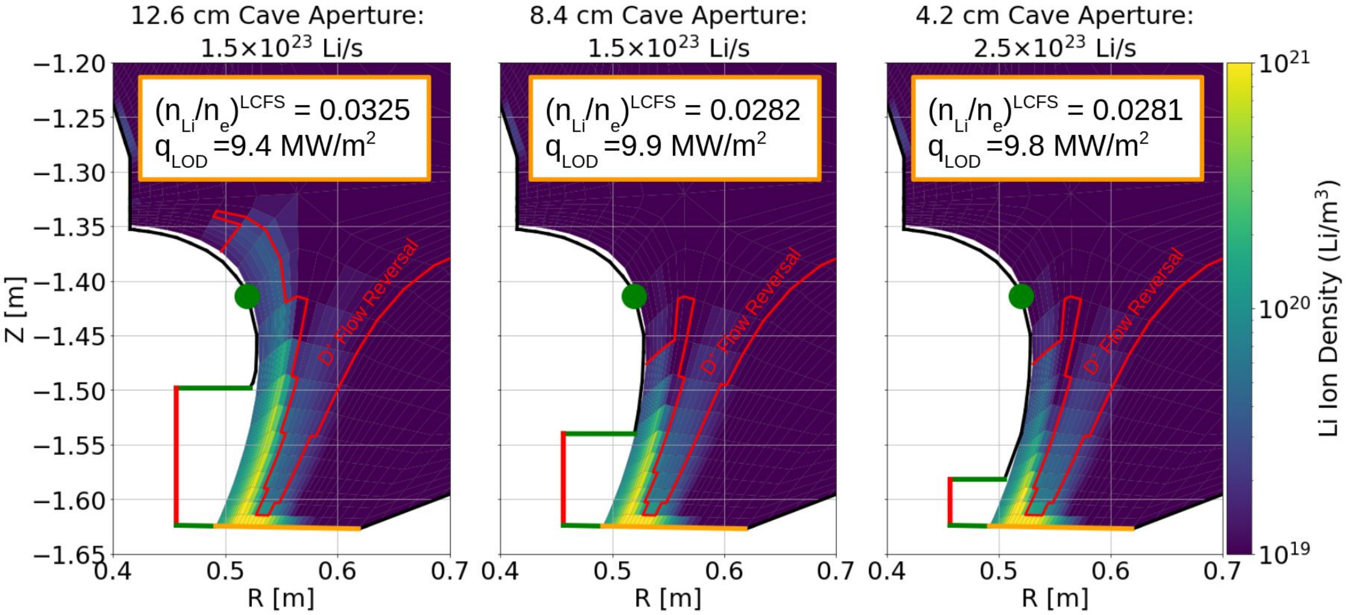
- The lithium vapor box can be simplified to a private flux region lithium vapor cave in NSTX-U
- With the full PFR structure and HFS gas puffing, drift-enabled simulations showed both the inner and outer targets could have $q^{Tar} < 10$ MW/m^2 with $(n_{Li}/n_e)^{LCFS}$ as low as 0.013, down from $\sim$90MW/m^2 unmitigated
- Now ready to begin engineering integration





Back-Up: Modeling Indicates The Vapor Cave Design Is Robust to Assumed Cave Height and Depth

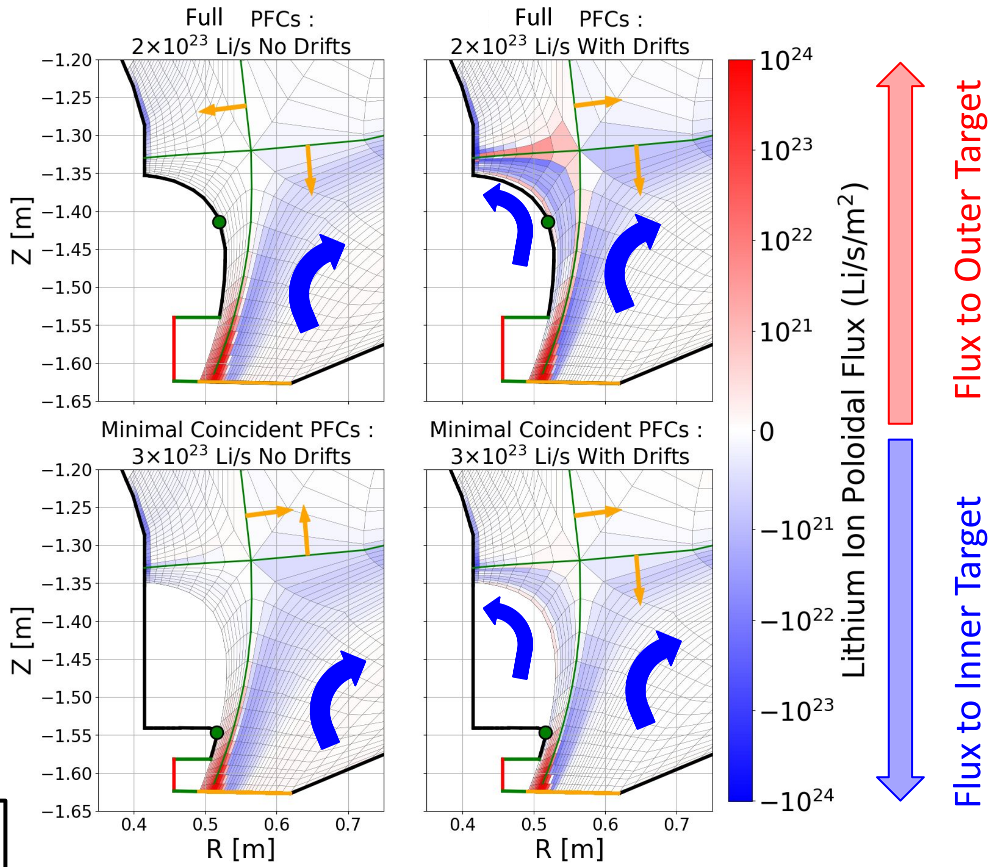
- Changes to cave aperture height and depth yielded only small changes to predicted upstream lithium concentration



E.D Emdee et al. Nuclear Materials and Energy 46 (2024) 101737

Li Flow Depend on Drifts

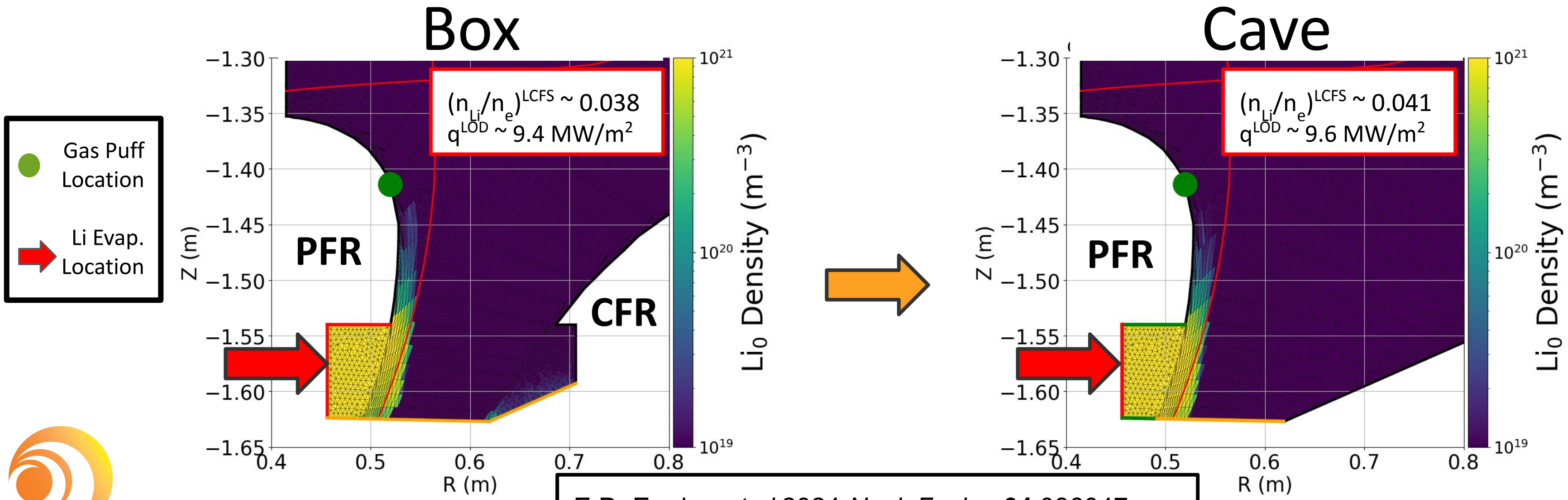
- When drifts are turned on, flow of lithium towards the inner target is observed
  - Similar to other observation of drifts in SOLPS



E.D Emdee et al. Nuclear Materials and Energy 46 (2024) 101737

Previous Optimization Demonstrated the Far SOL baffles are an unnecessary complication

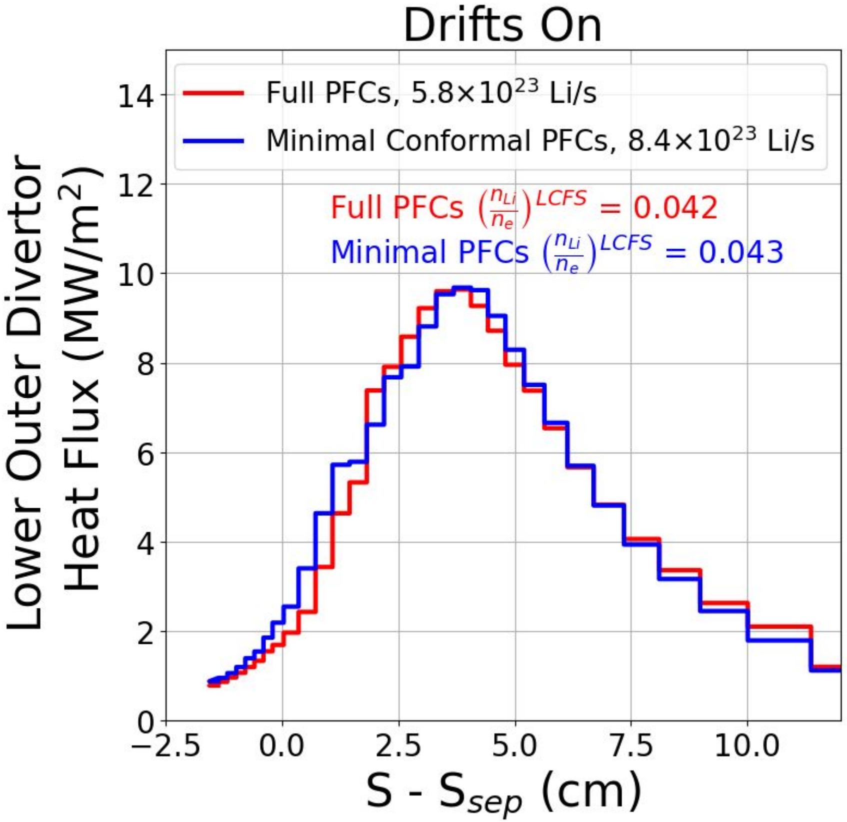
- The removal of the Common Flux Region (CFR) baffles is now referred to as the lithium vapor “cave” as we no longer have the full box structure of the lithium vapor box



E.D. Emdee *et al* 2024 *Nucl. Fusion* **64** 086047

Effect of PFC Design is Reduced With Drifts Turned On

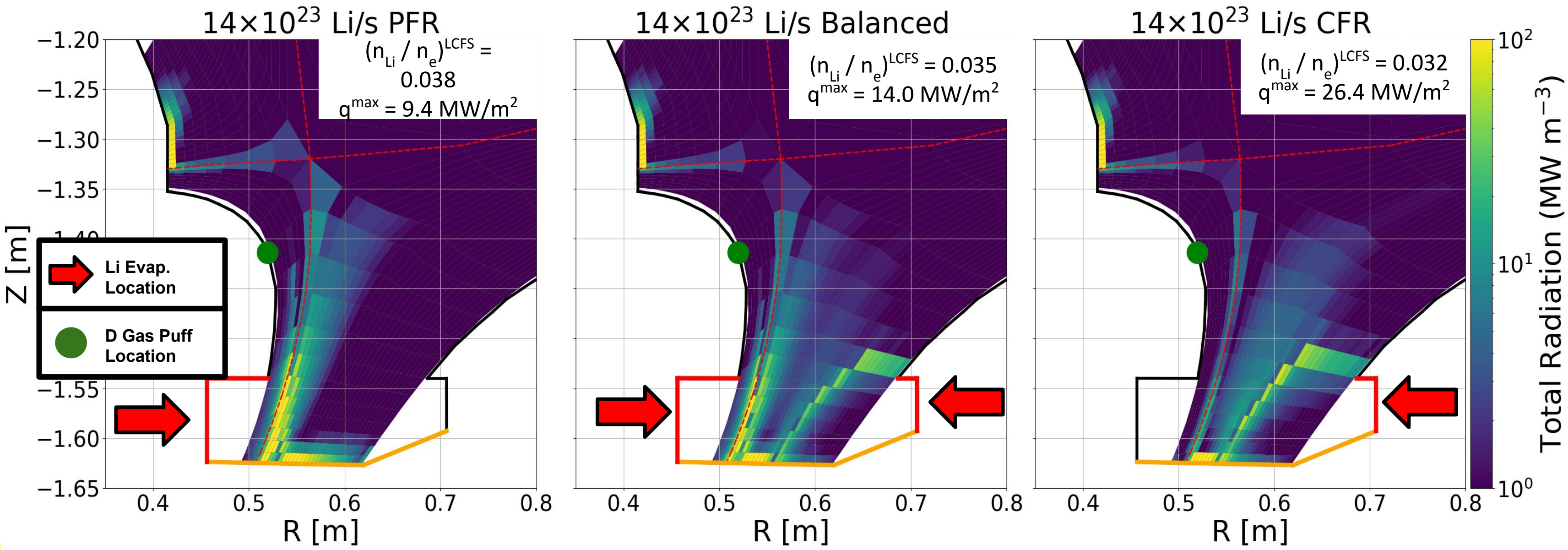
- For a similar lower outer divertor heat flux, both PFC designs get similar lithium concentrations at the LCFS when drifts are turned on



E.D Emdee et al. Nuclear Materials and Energy 46 (2024) 101737

Private Flux Region Evaporation Causes Radiation at Separatrix, resulting in q^{max}<10 MW/m^2

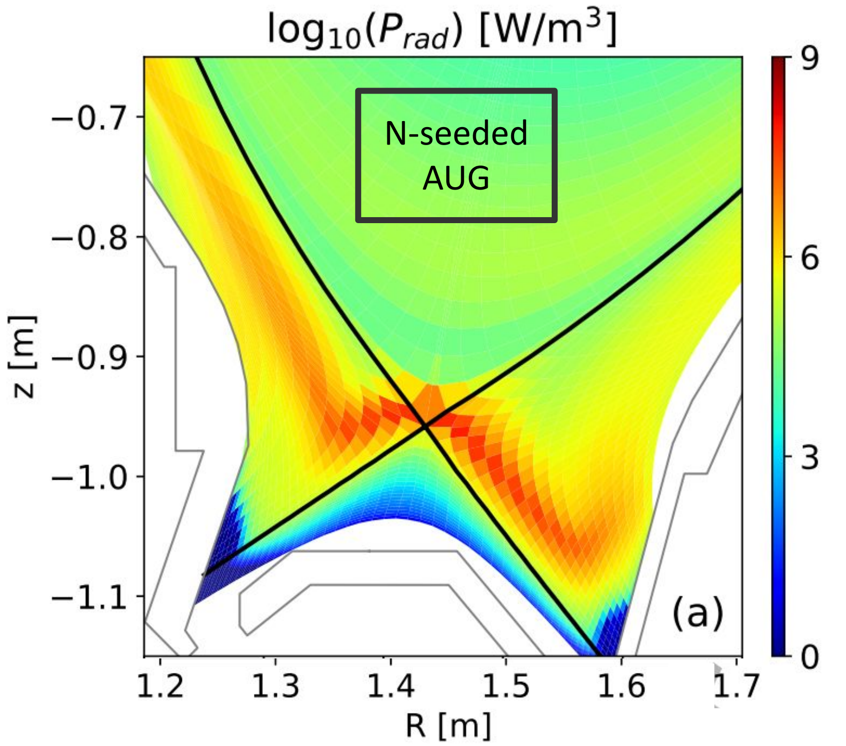
- Meanwhile evaporation from the CFR was ineffective at heat flux reduction, preventing sufficient heat flux mitigation



E.D Emdee et al. Nuclear Fusion 64 (2024) 086047

Divertor Detachment Can Be Problematic

- Divertor detachment typically induced via controlled impurity seeding (e.g N, Ne, Ar, Xe)
- Divertor detachment with medium-Z impurities has the tendency to create a highly radiating region at the X-point
  - Can reduce core & pedestal performance
  - Heat flux reduction can be maintained, though often at the cost of high Z_{eff}
- Goal: create a detached divertor that confines radiation and impurities closer to the target



O. Pan *et al* 2023 *Nucl. Fusion* **63** 016001