Development of a Lithium Vapor Box Divertor for Controlled Plasma Detachment

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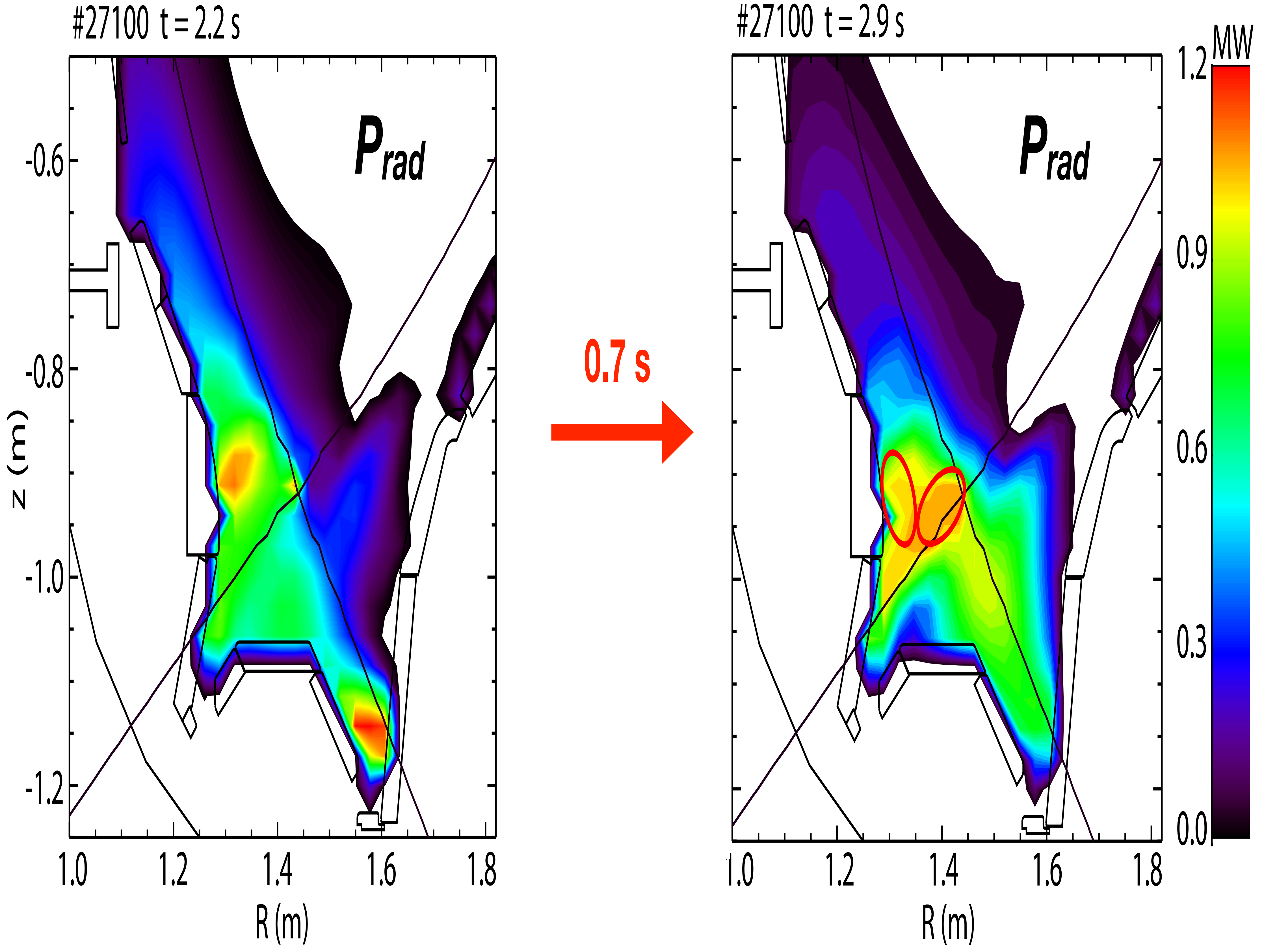
Divertor Detachment Front
Easily Runs up to the Main Plasma

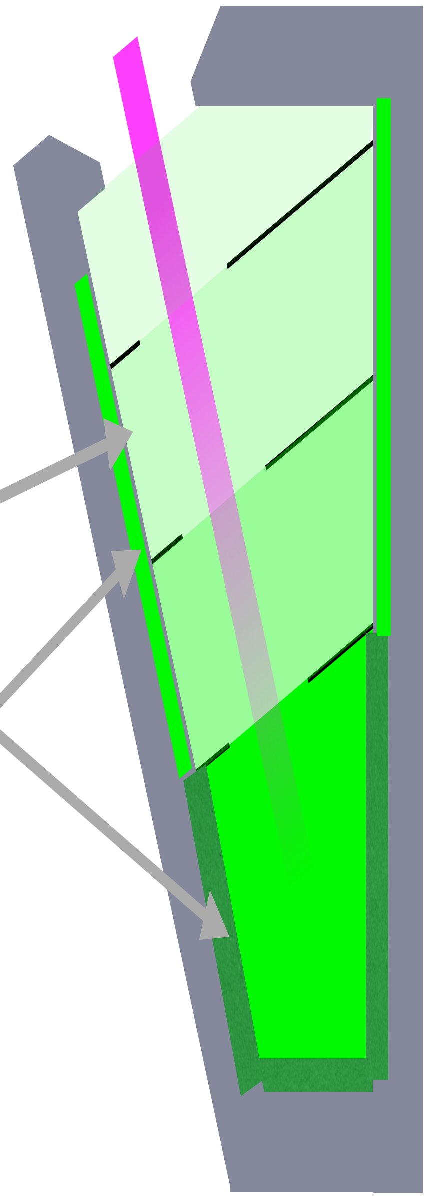
Potzel, NF 2014, AUG



Deleterious effect on H-Mode pedestal.

Lithium Vapor Box Divertor Concept

- Provide a localized cloud of Li vapor away from main plasma
  - Evaporation at ~ 750° C
  - Condensation at ~ 3-400° C (determines DT pumping)
- Return liquid lithium to evaporator.
- Creates strong vapor gradient.
  - Detachment front cannot run up to x-point.
  - Detachment front location is resilient to variable heat flux.
- Cannot be achieved with gaseous impurities – pumping is too weak



UEDGE Model with Lithium

- UEDGE has a purely diffusive model for lithium vapor transport.
  - Based on collisions of lithium atoms with plasma ions. No Li-Li collisions.
  - Inaccurate in regions dominated by lithium convection/viscosity: Navier-Stokes regime.
- Transports lithium in plasma, calculates radiation self-consistently.
  - Issues with thermal force model at high impurity fraction.
- Achieves detached plasma in Fusion Nuclear Science Facility (FNSF) with nearly 100% lithium radiated power. In "real" world would include other (seed) impurities.
  - Upstream lithium fraction depends on upstream electron density.

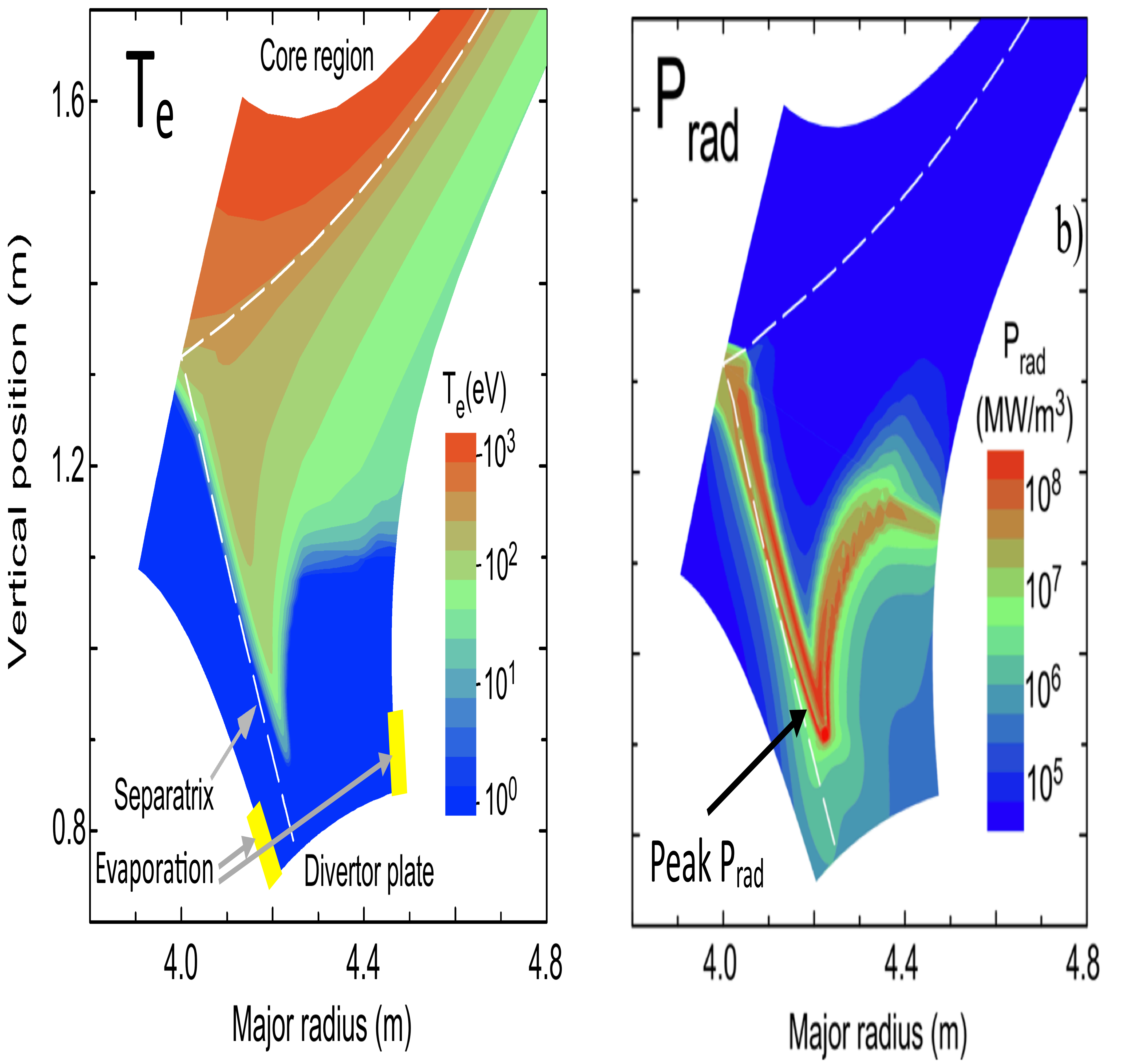
UEDGE Predicts Detachment in FNSF with Lithium in Simplified Divertor

0.5 m outer divertor leg, Open geometry

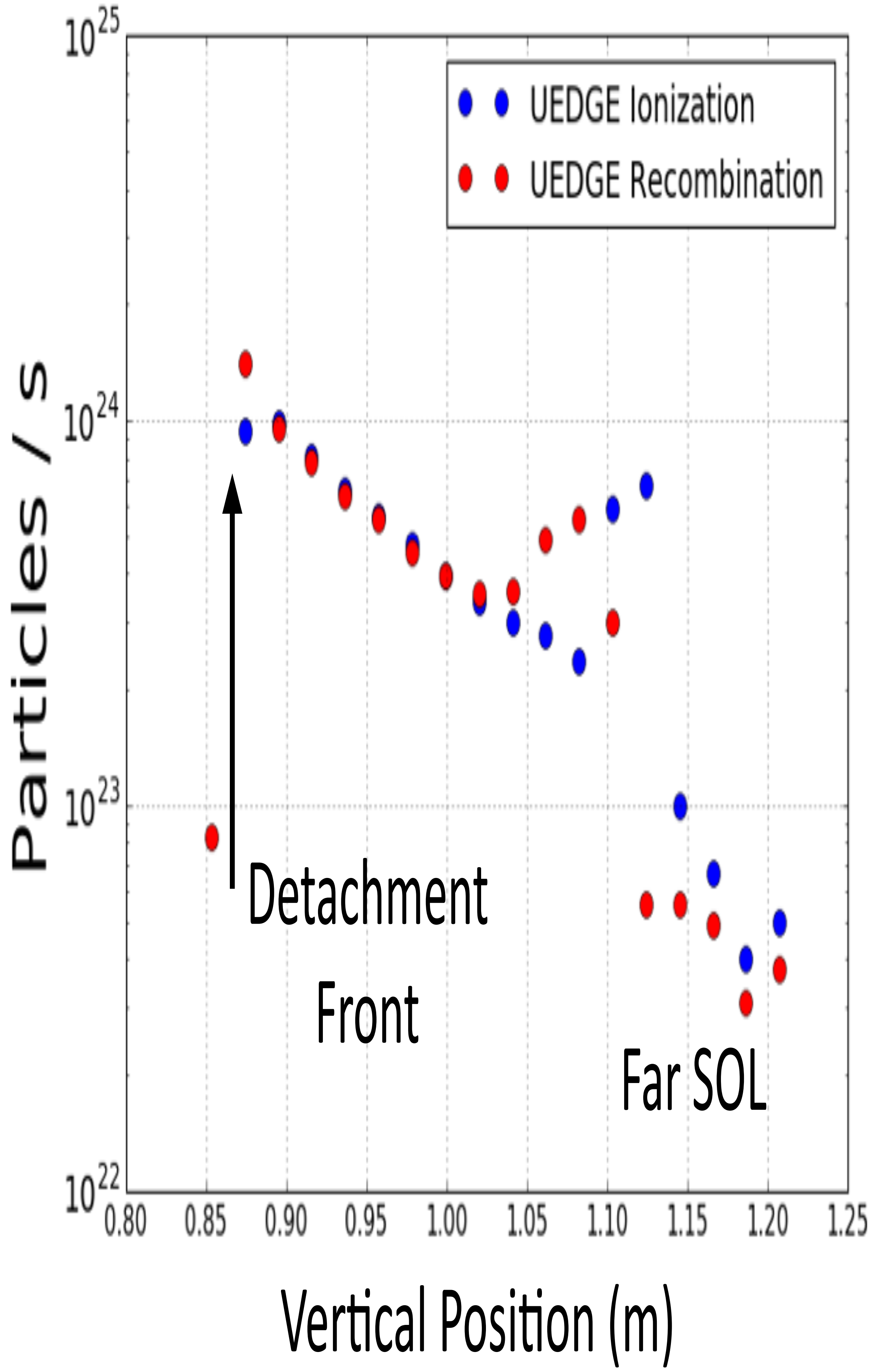
Localized evaporation, absorbing walls.

60 eV radiation per ionization

Divertor region heat flux All radiative! ~ 2 MW/m²



UEDGE Lithium Ionization & Recombination in Near Local Balance

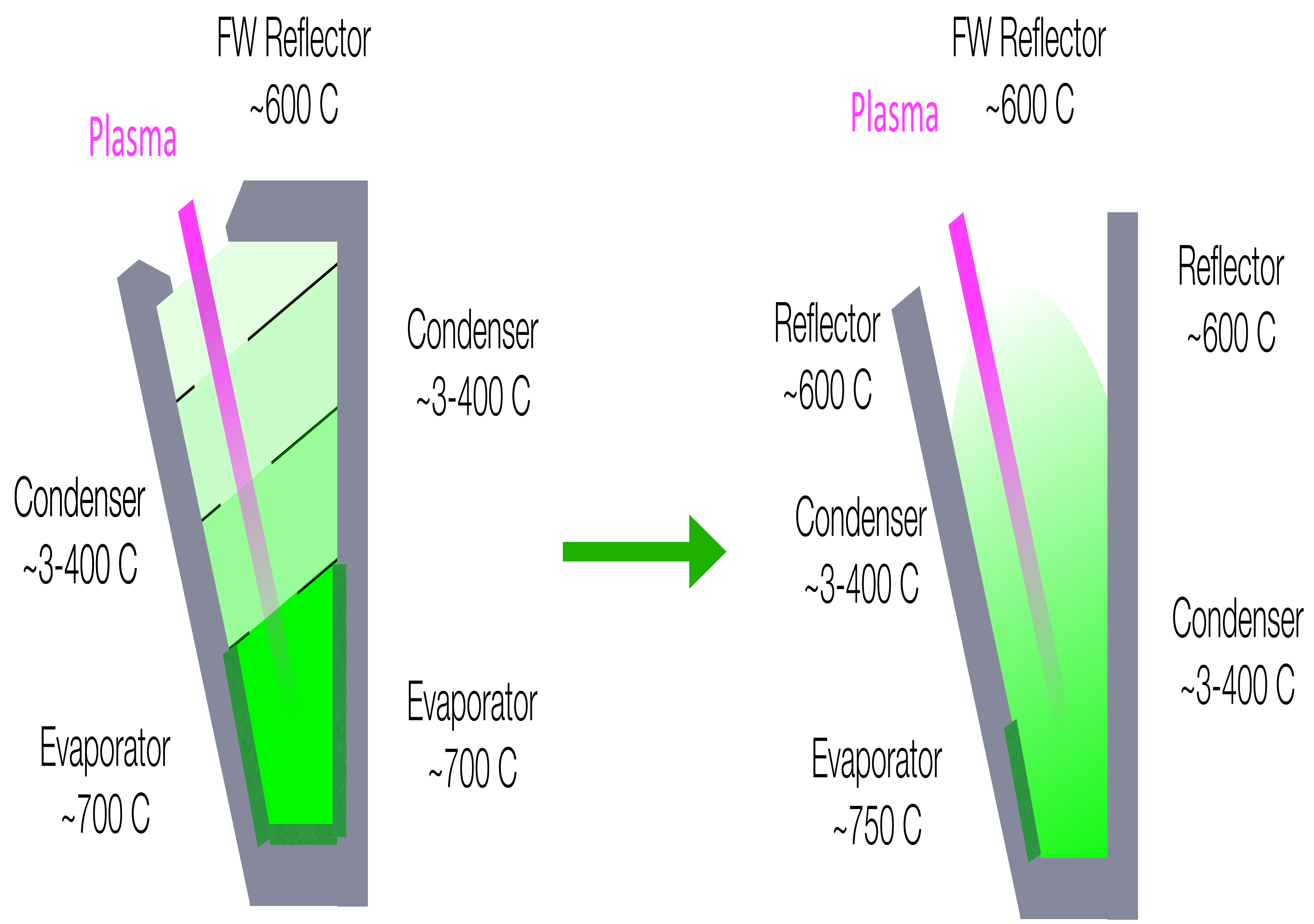


Recombination roughly equals ionization at a given Z position.
In effect, plasma acts like a mirror (with a cricket bat).

SPARTA Provides Alternative Model for Lithium Vapor, including Convection & Viscosity

- Using SPARTA Monte-Carlo Direct Simulation code for lithium vapor
  - Li-Li collision model based on known vapor viscosity vs. T.
  - Model evaporation and condensation based on known equilibrium Li pressure vs. T, and Langmuir fluxes from surfaces.
- Lithium – Plasma interaction
  - Assume absorption of lithium at $T_e = 0.2$ eV
  - Recombination at the same point.
    - Lithium leaves along B with $T_{Li} = E_{||,Li} = 0.2$ eV

A Simplified Lithium Vapor Box Divertor Based on UEDGE Results



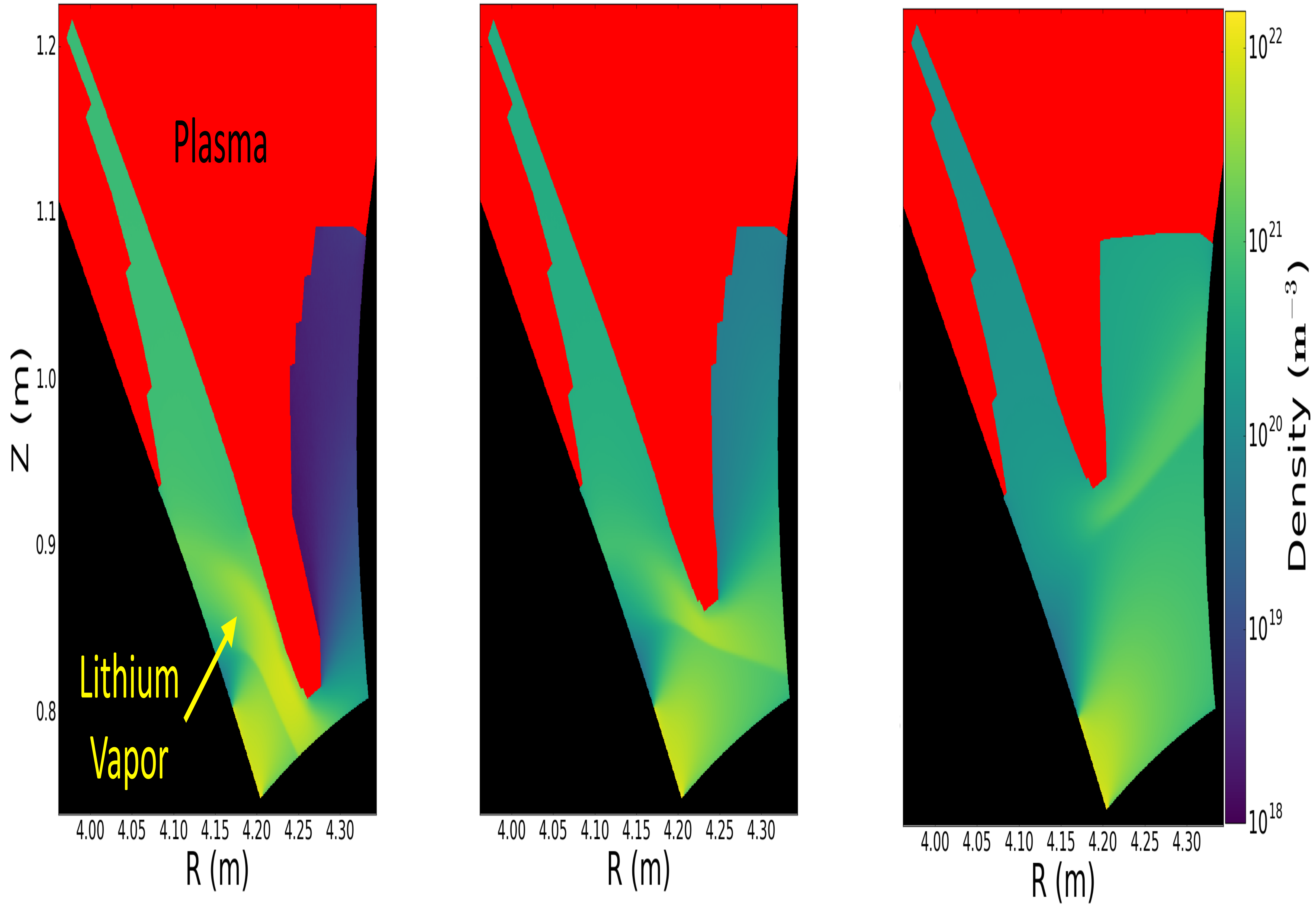
Allows more Li efflux, but needs less total evaporation

Makes experimental implementation easier, including starting with a toroidal segment

Lithium Accumulation on First Wall will be Very Low

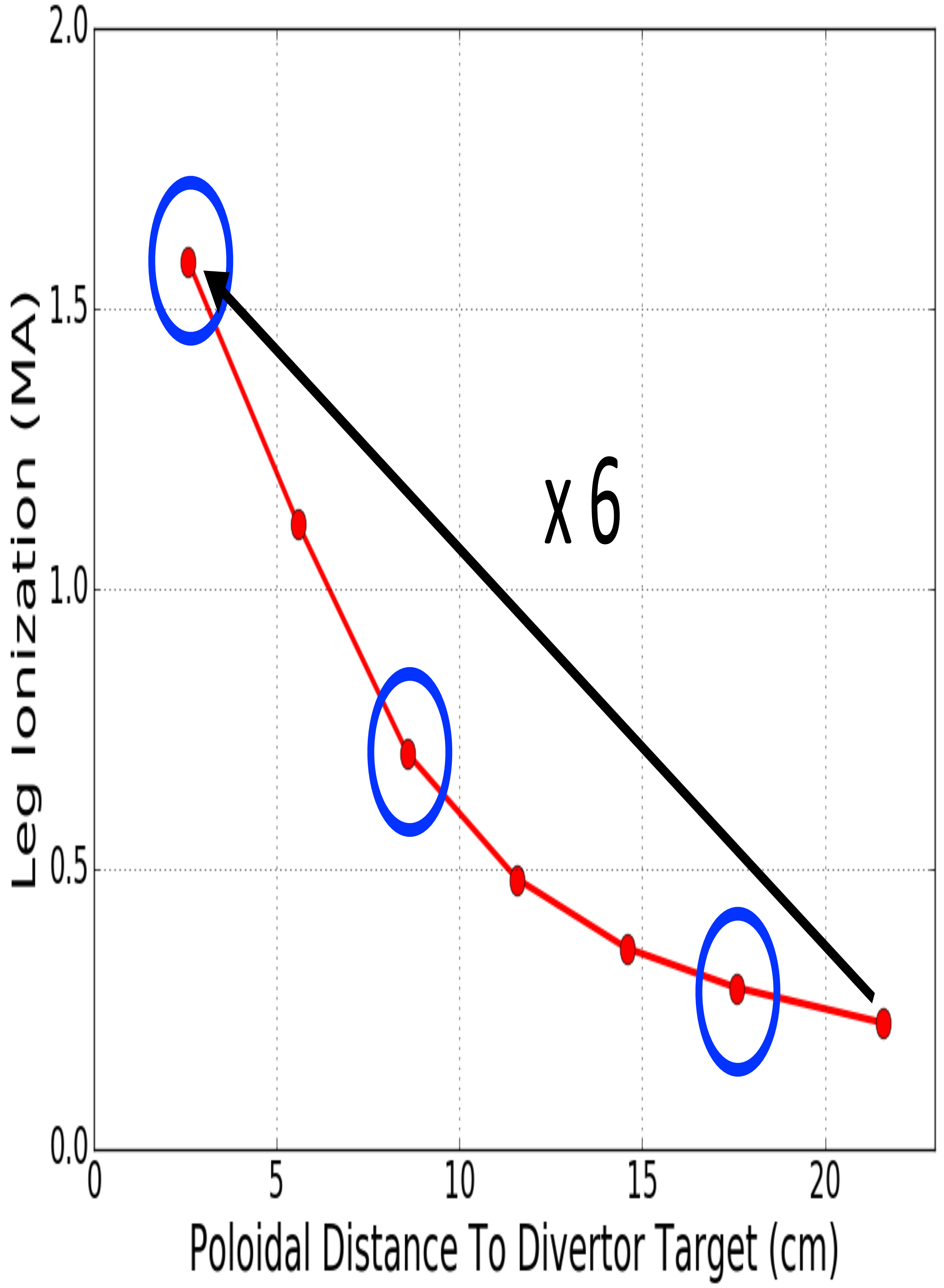
- 140 g/s of lithium evaporated for P_{rad} = 66 MW.
- Assume all of this is deposited on first wall, $T_W \sim$ 600 C.
- Evaporation rate at 600 C = 2.66 g/s/m^2
- Area of first wall ~ 300 m^2
- Total evaporation rate with multi-monolayer surface coverage = 800 g/sec
- Can't even accumulate a few monolayers of Li
- LiH decomposes in << 1 sec at 600 C.

SPARTA Shows Strong Variation in Lithium Absorption with Detachment Vertical Position



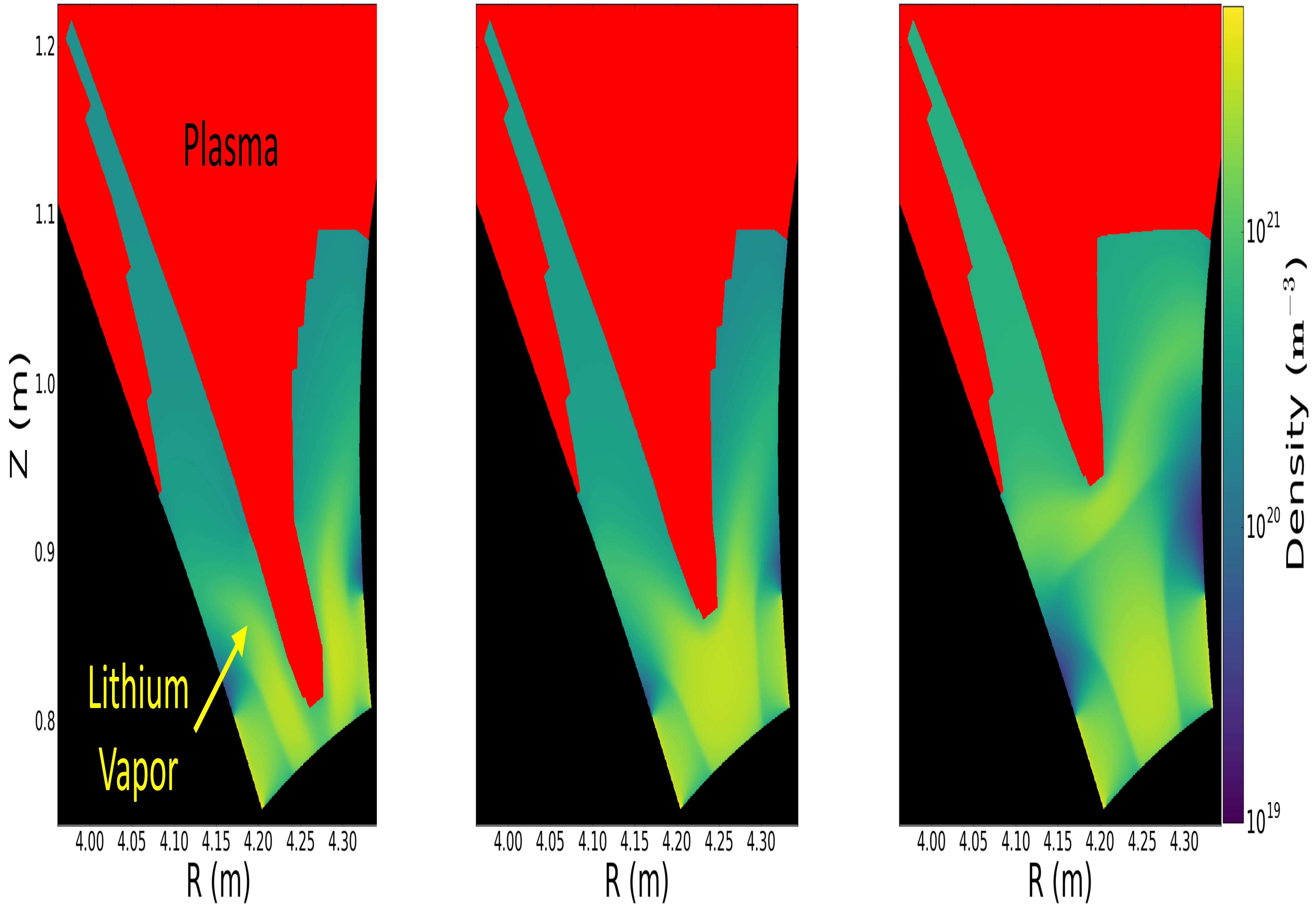
Lithium evaporation from private flux side is much more efficient when leg is closer to evaporator.
(Does not include radiative heating of evaporator.)

SPARTA Gives Very High Positional Resilience



Lithium injection from private flux side is much less efficient as leg moves away from evaporator → Positional resilience. (Does not include change in radiative heating of evaporator.)

Two-Sided Injection Has Low Resilience



Little variation in Li absorption as leg moves away from evaporators. Same low resilience with bottom evaporation.

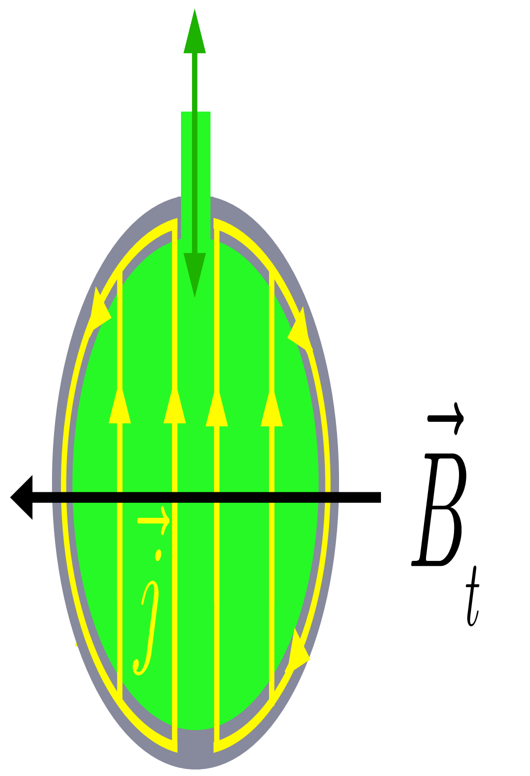
Lithium Return Flow is Determined by Balance between Capillary Pull & MHD Drag

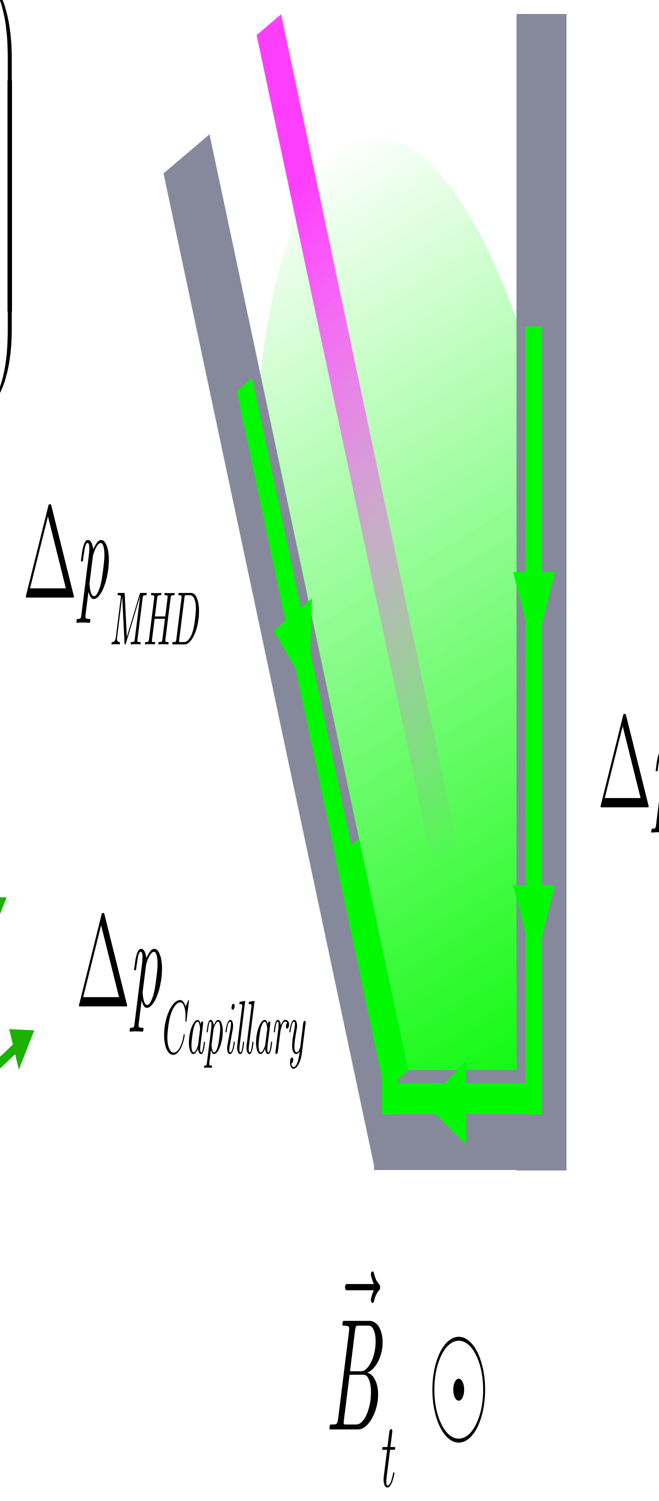
$2a_{Li} = \text{pipe ID}$

$t_w = \text{wall thickness}$

$$\Delta p_{Capillary} = \frac{2\gamma\cos\alpha}{r_p} \geq \Delta p_{MHD} =$$

$$\int \vec{j}_{Li} \times \vec{B} \cdot d\vec{l} = \int v\sigma_{Li} B^2\, dl \left(\frac{\sigma_w t_w}{\sigma_{Li} a_{Li} + \sigma_w t_w}\right)$$

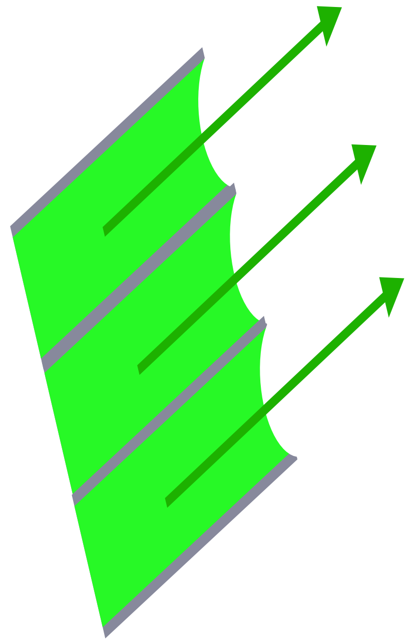


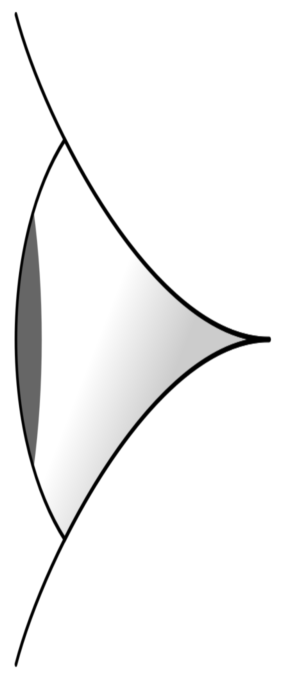


$\gamma \equiv \text{surface tension}$

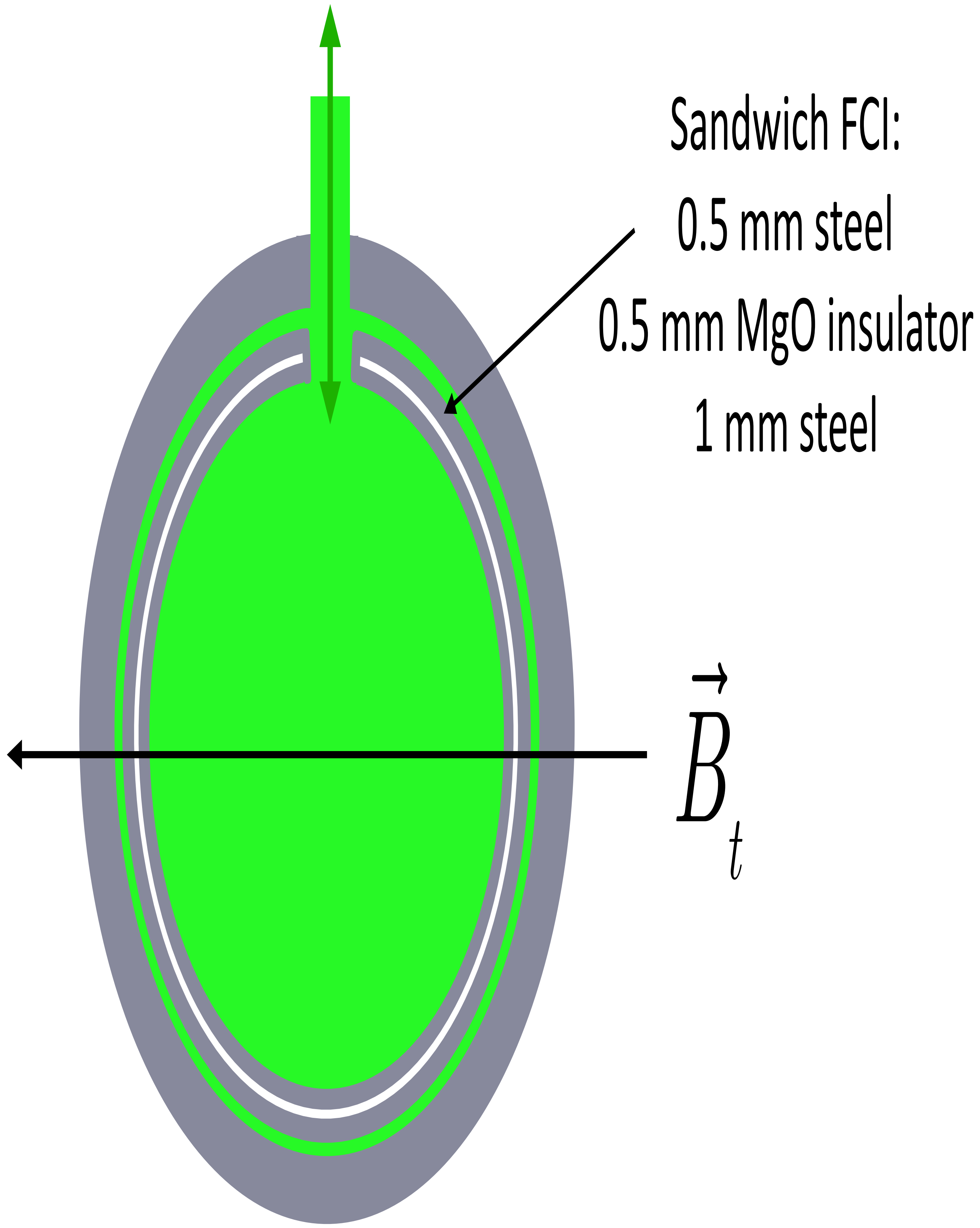
$\alpha \equiv \text{contact angle}$

$r_p \equiv \text{pore radius}$





Sandwich Flow Channel Inserts Reduce ΔP_{MHD}



$2\,cm\,ID\;pipes\;spaced$

$10\,cm\;apart\;toroidally$

$$\Delta p_{MHD} = 0.22\,\Delta p_{Capillary}$$

$$@r_p = 40\,\mu m$$

$$v \leq 2.9\;mm/s$$

$$\phi = 0.4\,mV$$

Gap in Flow Channel Insert orients towards divertor surface.
Works top and bottom, leaves margin for other effects.

Conclusions

- UEDGE predicts detachment in FNSF with Li alone, shows lithium dynamics at detachment front.
- This provides a preliminary physics basis to optimize Lithium Vapor Box Divertor using SPARTA.
- A divertor with private-flux-side lithium evaporation near the bottom of the divertor leg –
  - Provides adequate lithium for detachment.
  - Provides strong positional resilience of the detachment front, without baffles. No issue of Li accumulation on 600 C surfaces.
  - Sandwich Flow Channel Inserts facilitate capillary force to return 140 g/s of lithium across 7T magnetic field.
- Integrated modeling, design, & experiments are needed.