Development of a Lithium Vapor Box Divertor for Controlled Plasma Detachment

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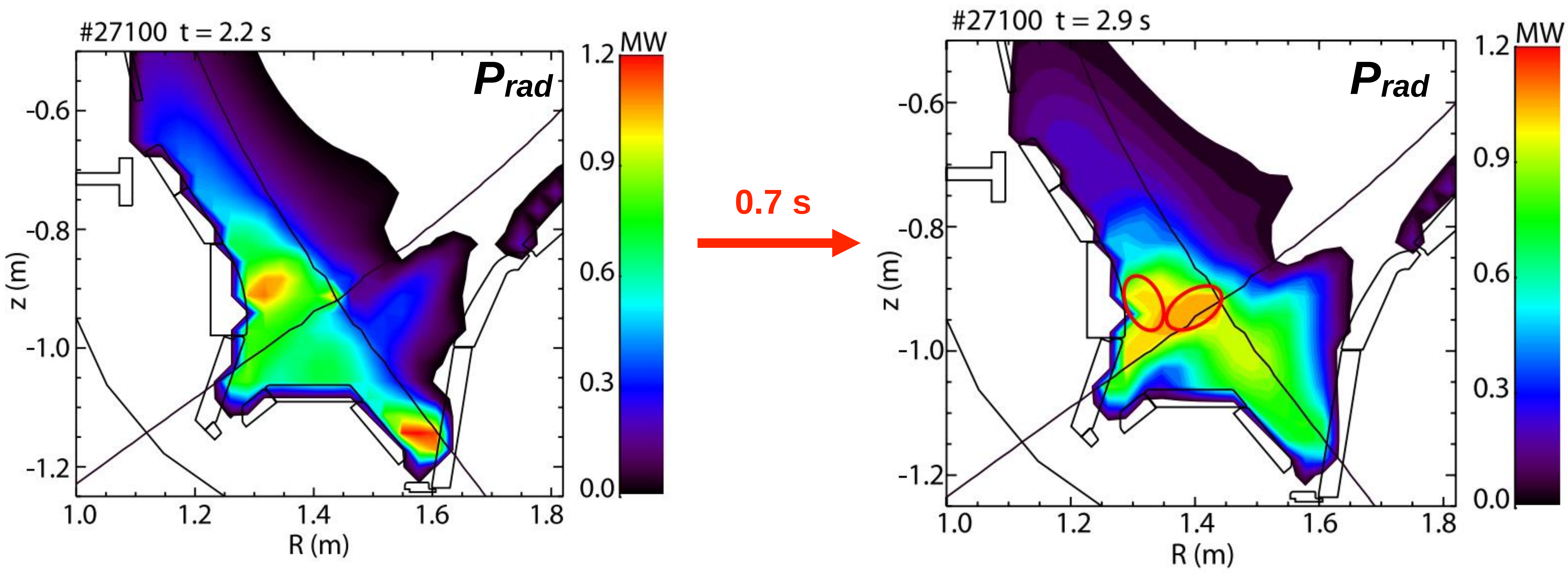
Divertor Detachment Front Can Run up to the Main Plasma

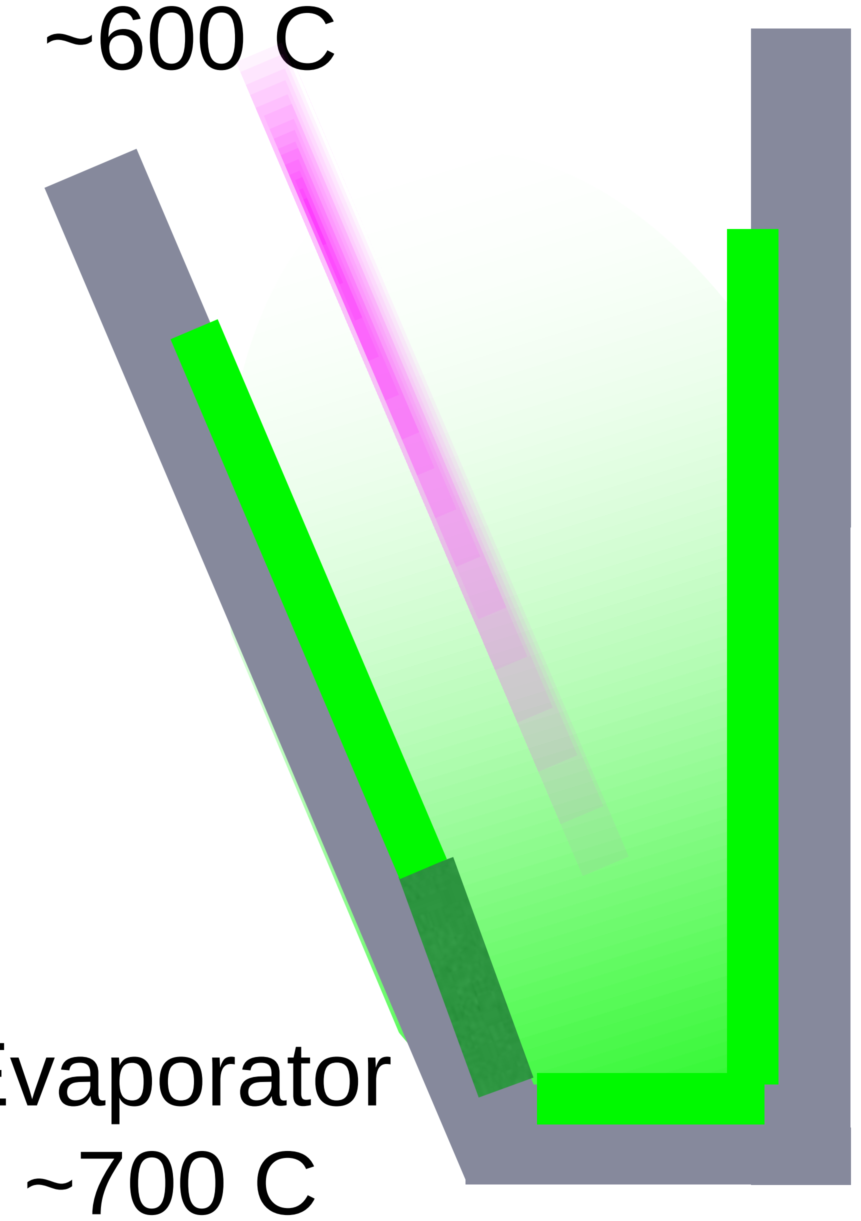
Potzel, NF 2014, AUG



Deleterious effect on H-Mode pedestal.

Lithium Vapor Box Divertor Localizes Radiation to Divertor Region

- Provides a localized cloud of Li vapor away from main plasma
  - Creates a strong detachment front to keep radiation in the divertor
- Creates strong vapor gradient so that 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
- Examined baffled configurations in the past but currently only considering no-baffle configurations



Two Codes to Capture Relevant Physics

- Difficult to capture all divertor physics with one code
- Used UEDGE to understand plasma-Li interactions
  - Diffusive model for particle transport
- Used SPARTA to understand Li-Li interactions
  - Direct Simulation Monte-Carlo code

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.
- Achieves detached plasma in Fusion National Science Facility (FNSF) with nearly 100% lithium radiated power and 66MW in outer divertor.
  - In "real" world would include other (seed) impurities.

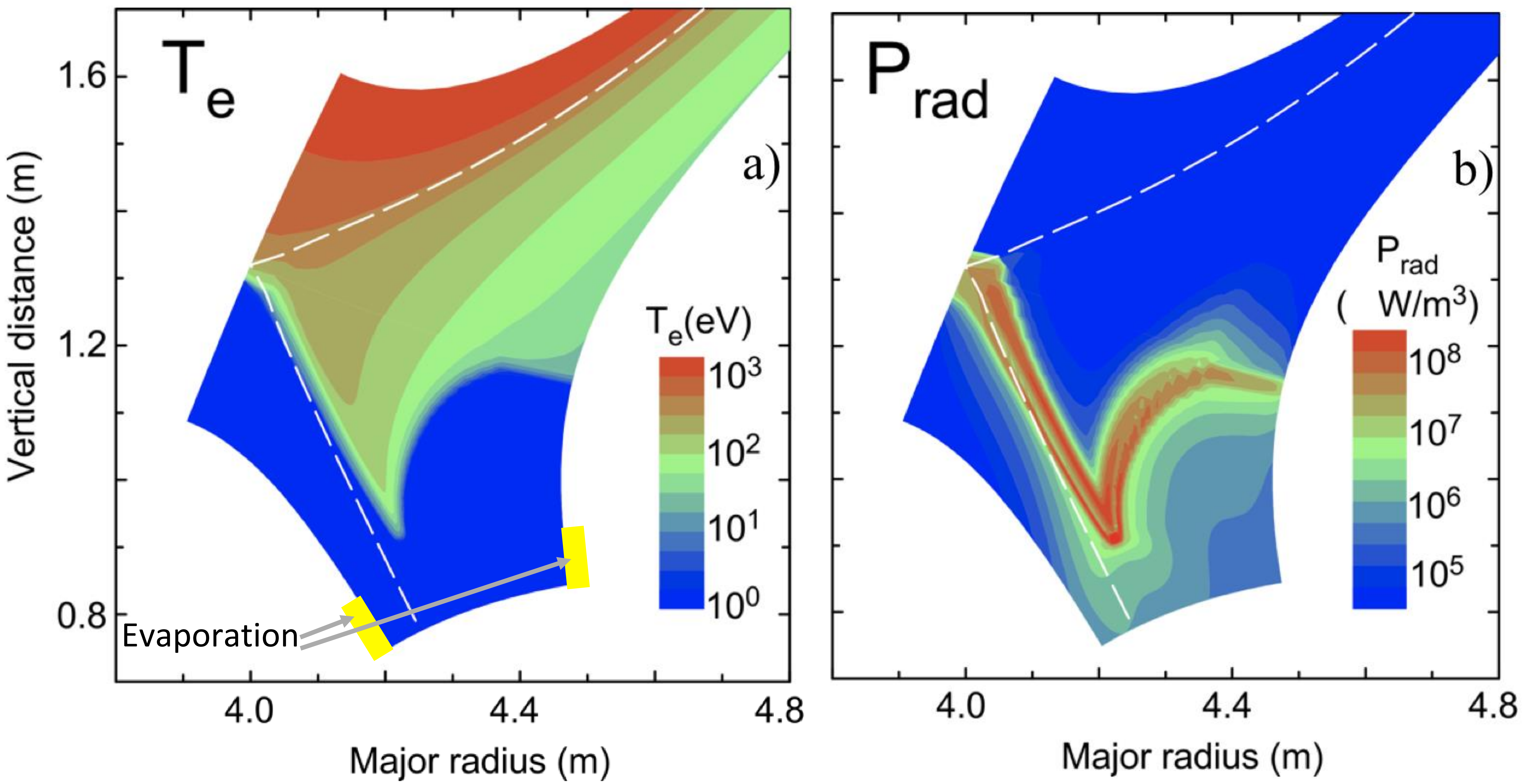
UEDGE Achieves Detachment in FNSF with Lithium

0.5 m Divertor leg, Open geometry

Localized evaporation, absorbing walls.

60 eV radiation per ionization

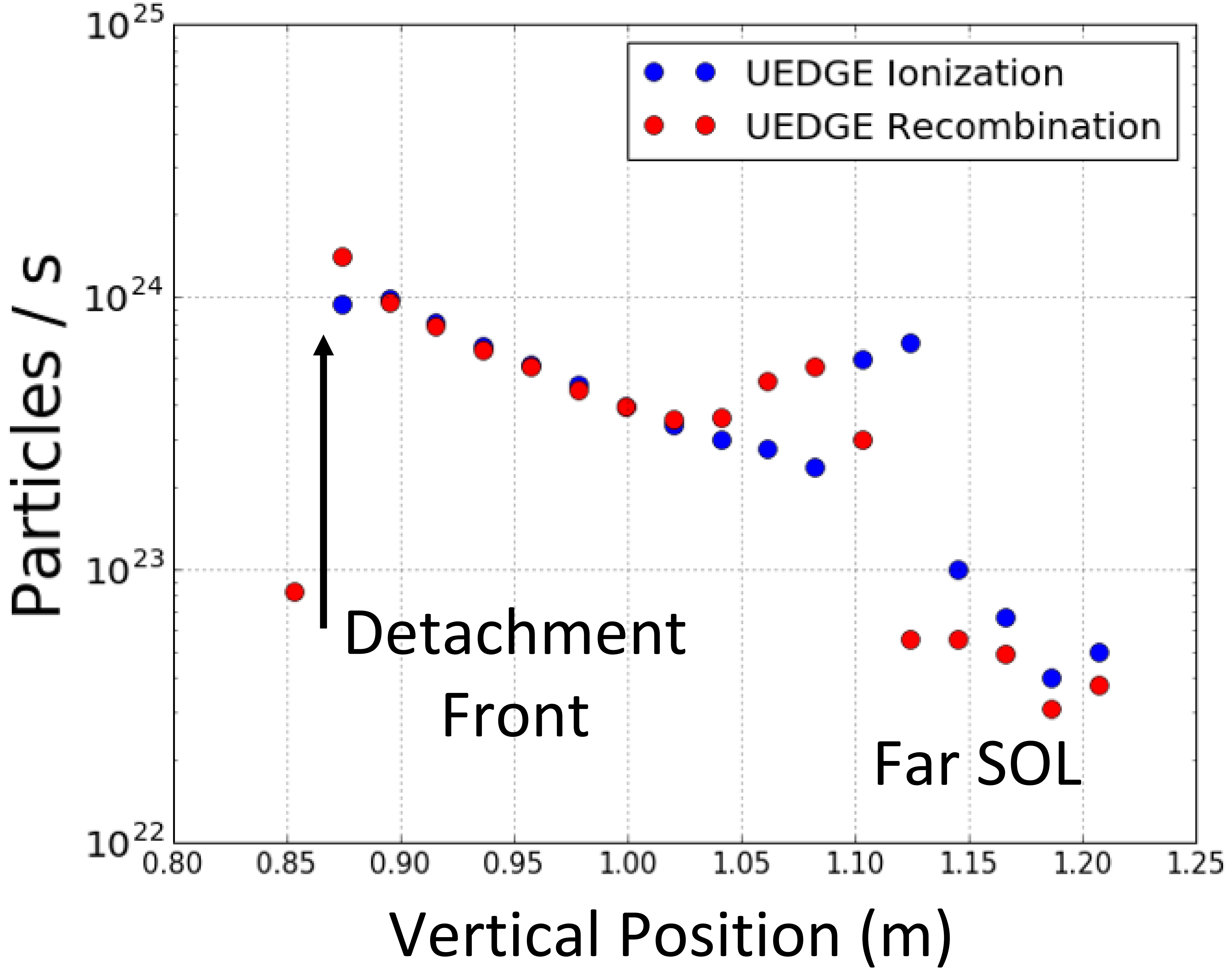
Divertor region heating ~ 2 MW/m^2



UEDGE Provides Boundary Conditions To SPARTA

- **Recombination roughly equals ionization at a given Z position**

- **In effect, plasma acts like a mirror but with an increase in particle energy**

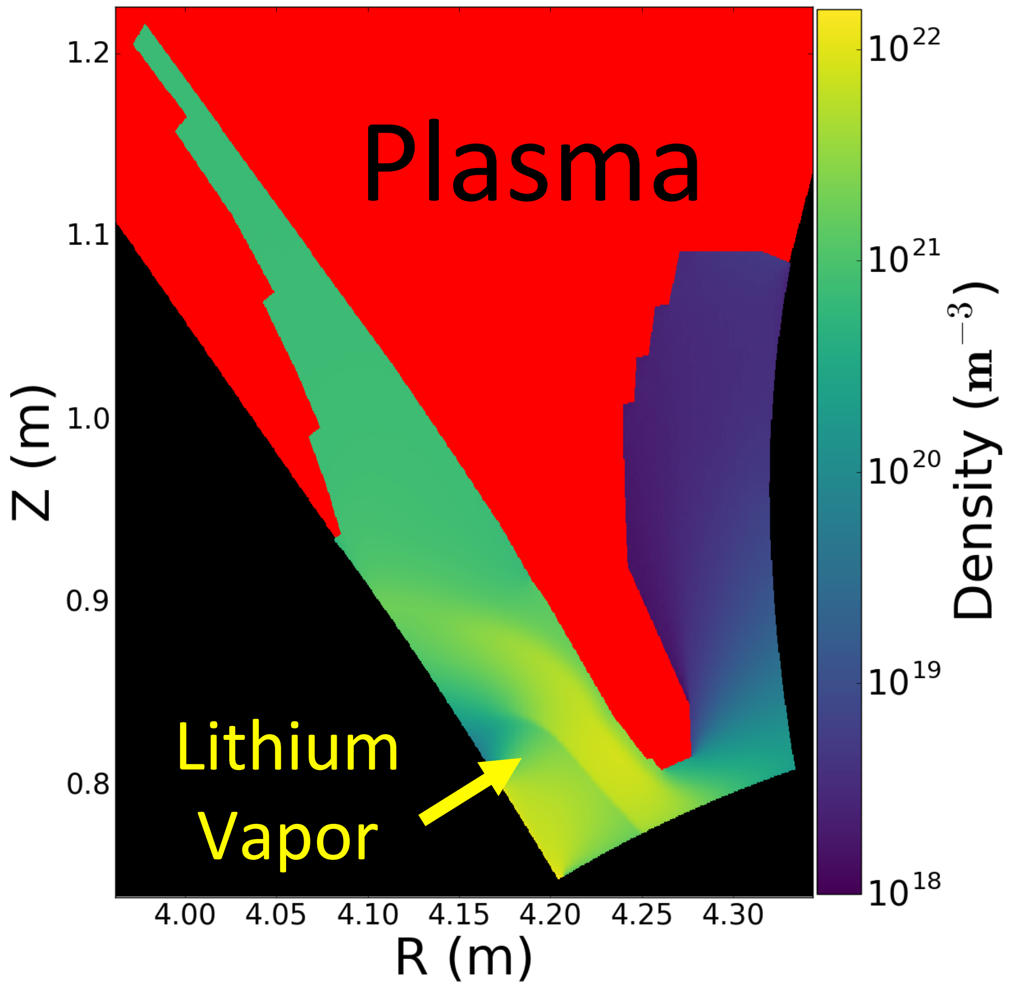


SPARTA Simulation Set-Up and Lithium-Plasma Interactions

- **Using SPARTA Monte-Carlo Direct Simulation code for lithium vapor**
  - **Li-Li collision model based on known vapor viscosity vs. *T* makes this valid for regions outside of plasma.**
- **Lithium – Plasma interaction taken from UEDGE results**
  - **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**
- **Use SPARTA to design the vapor box to achieve detachment position resilience (explained on next slide)**

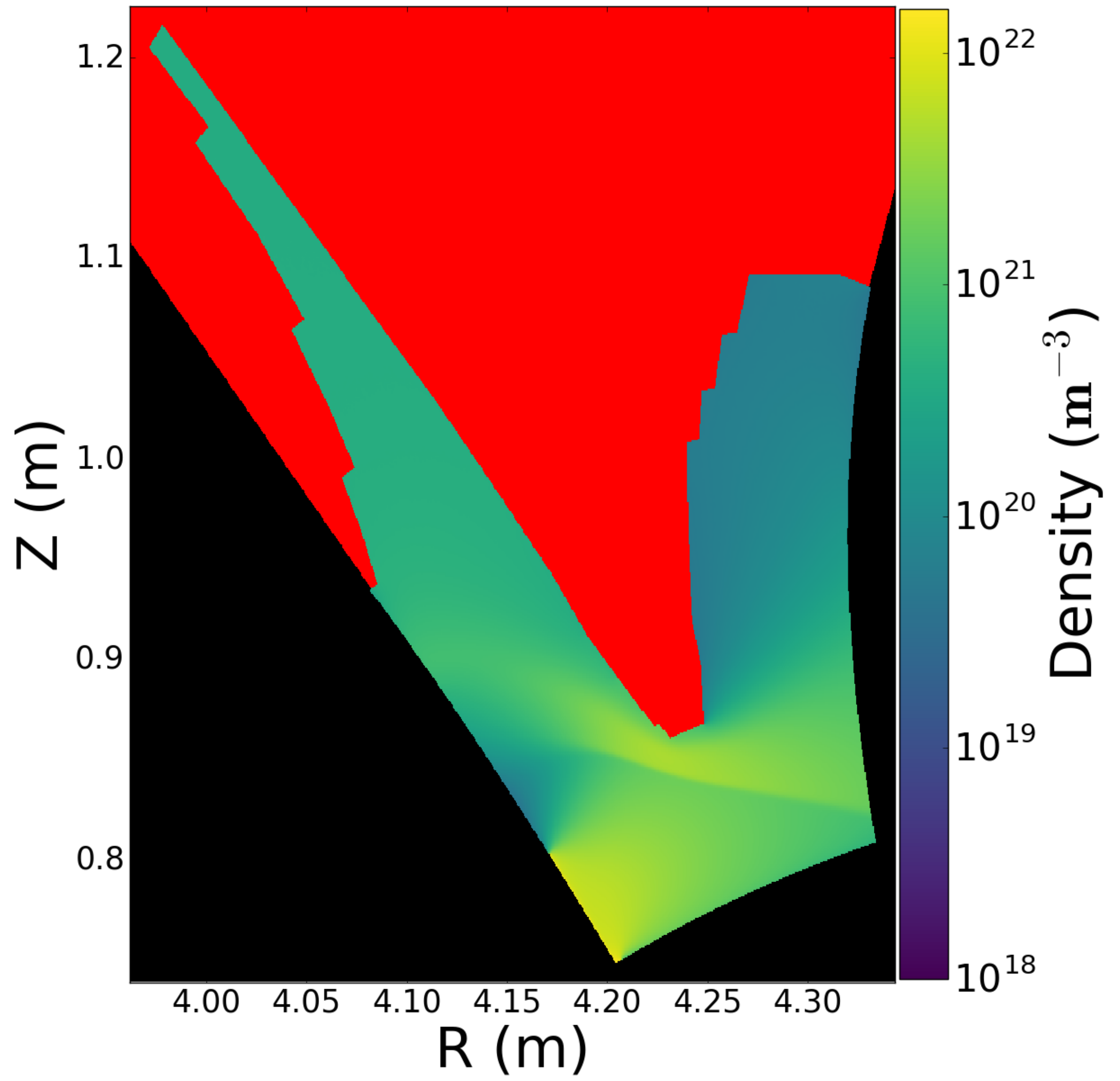
Detachment Position Resilience

High heat flux (high T_e) causes detachment front to extend towards divertor plate

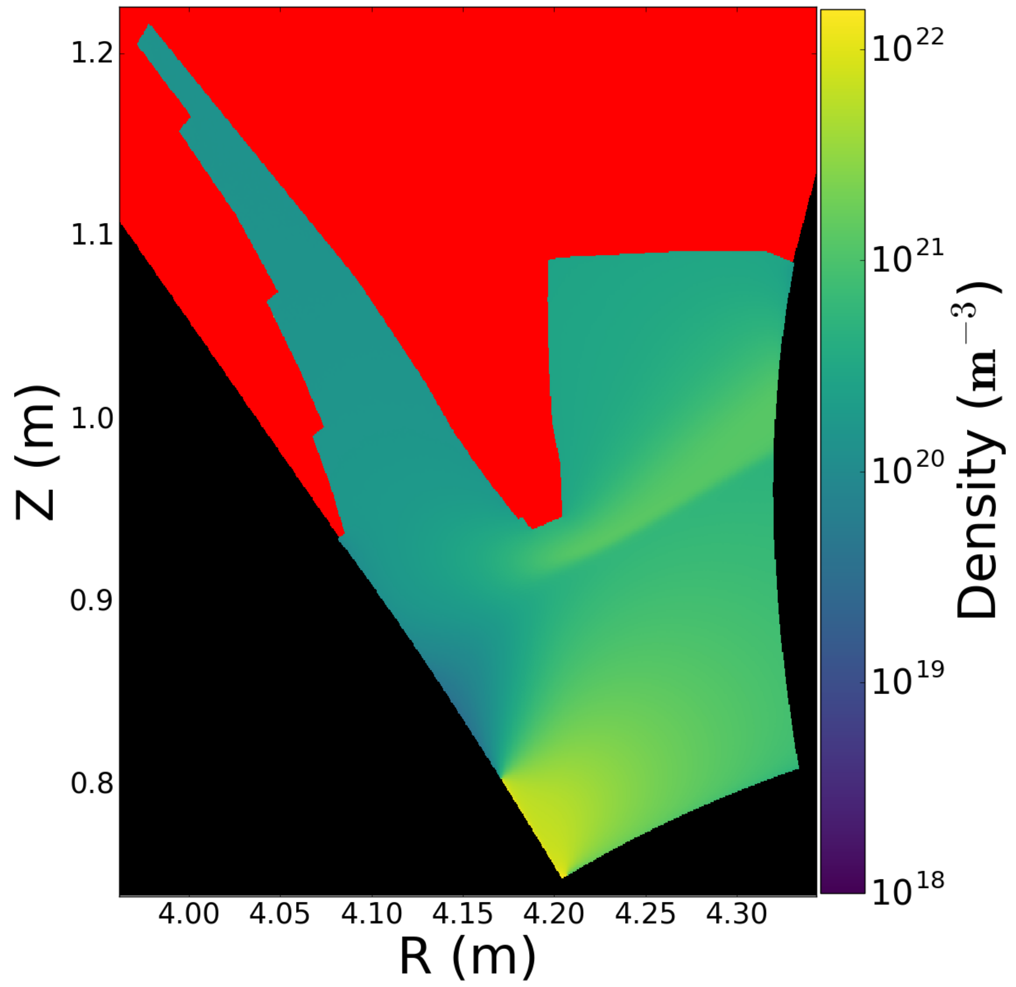


Extended detachment front causes more lithium ionization due to vapor gradient

Detachment front settles into, and resists changes to, equilibrium position

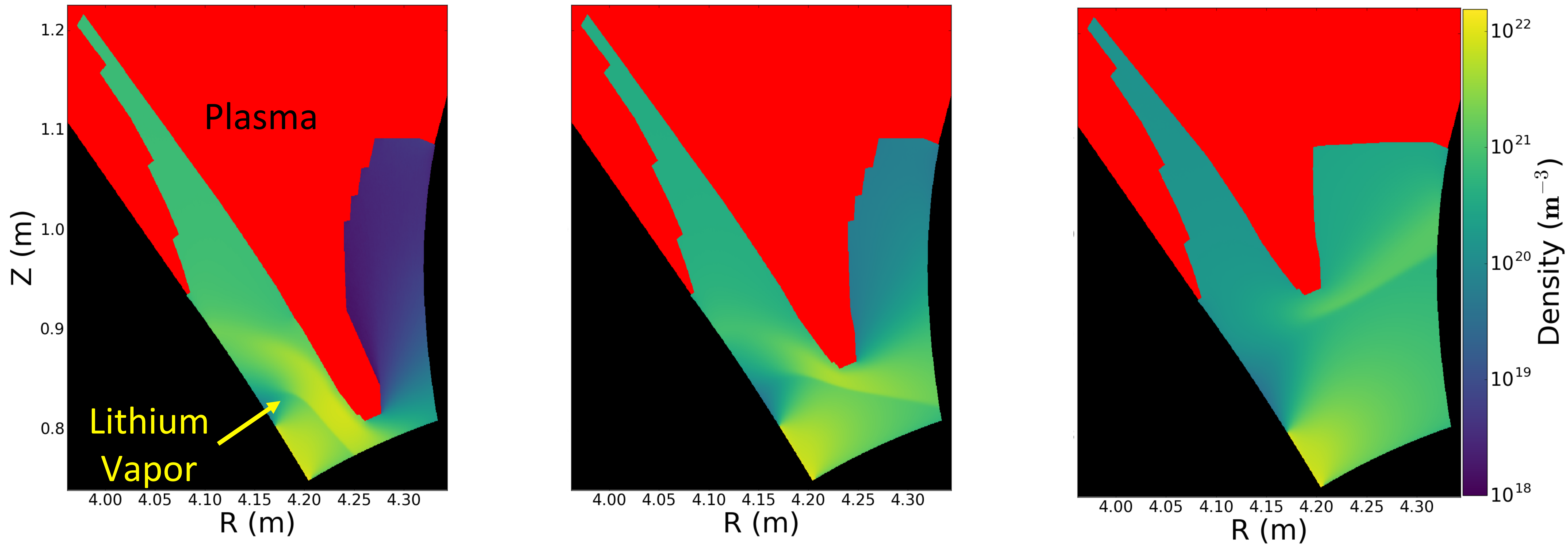


Low heat flux (low T_e) causes detachment front to retract towards X-point



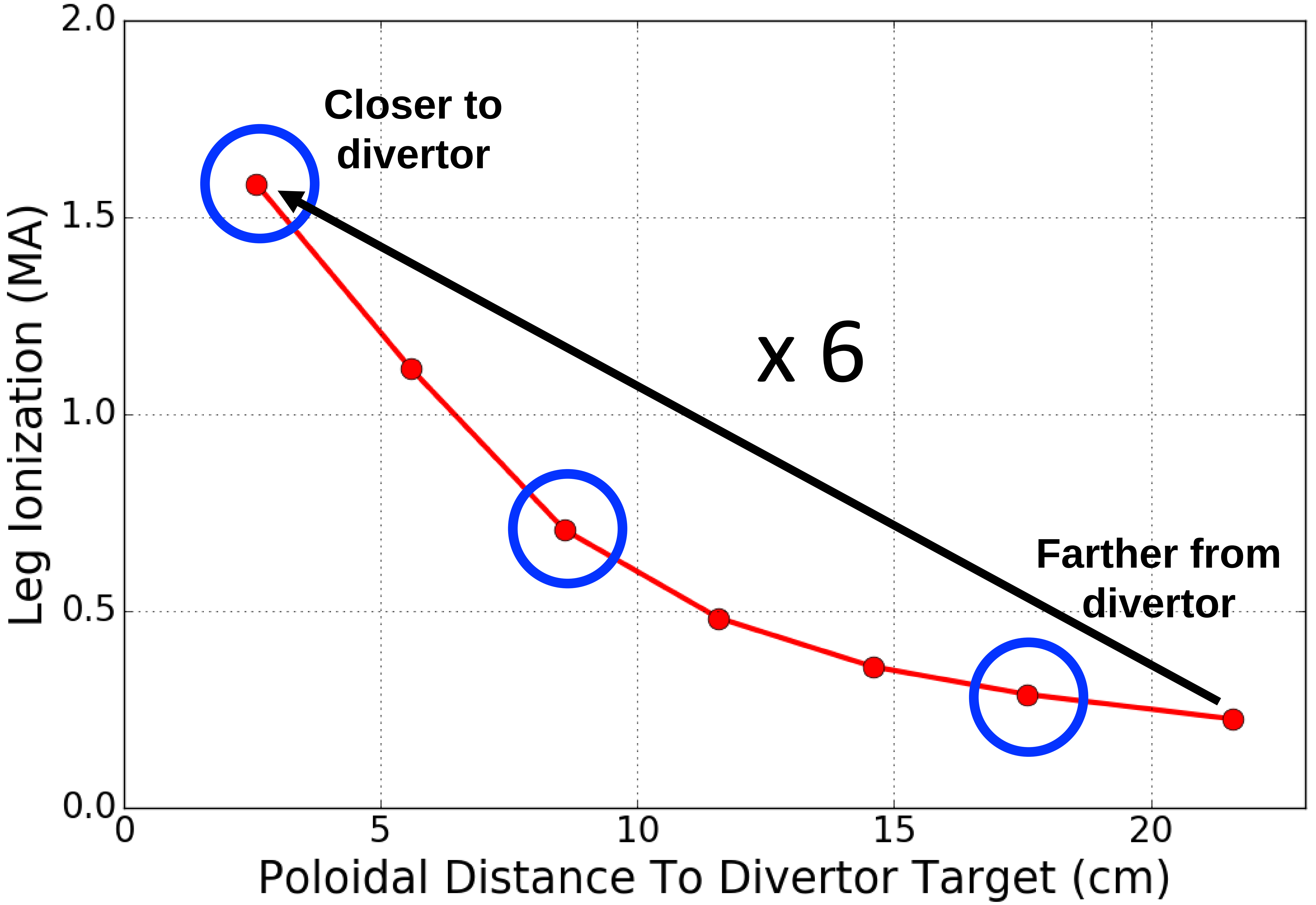
Retracted detachment front causes less lithium ionization due to vapor gradient

Using SPARTA to Demonstrate Detachment Position Resilience



- **Maintain constant evaporation rate**
- **Incrementally change plasma shape to simulate higher or lower heat flux**
- **Determine ionization rate of new configuration**

SPARTA Shows Vapor Box Has Very High Positional Resilience



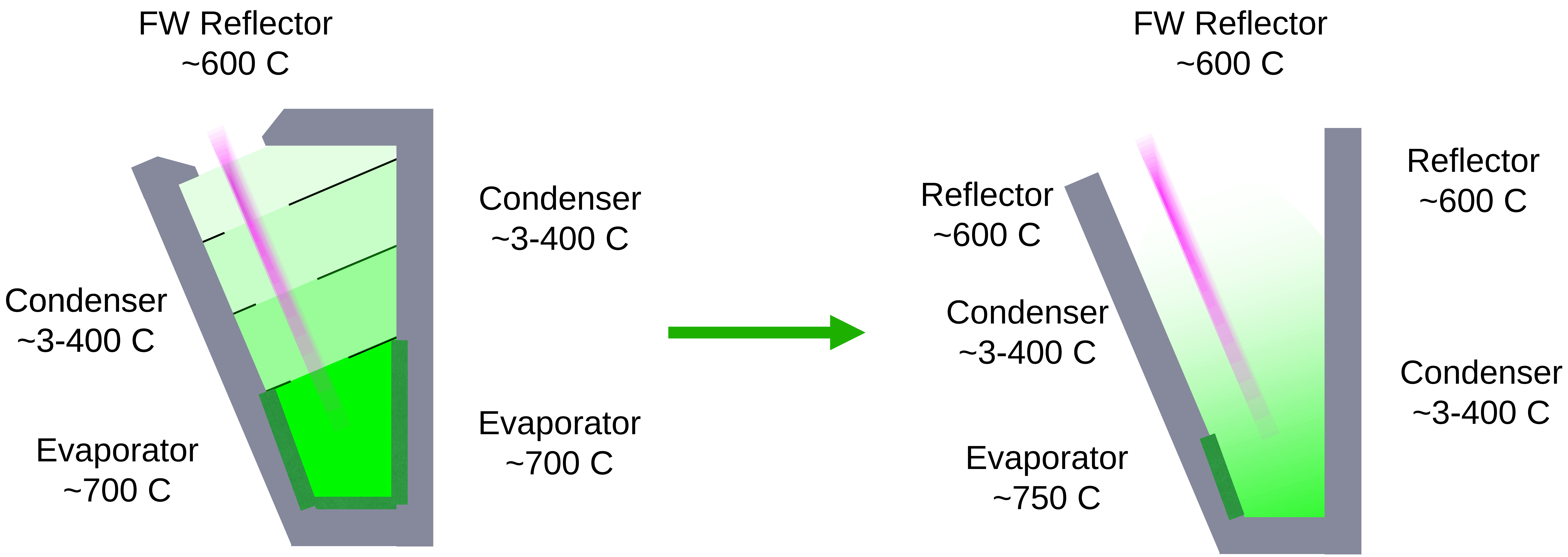
Lithium injection is 6x less efficient as detachment front moves away from evaporator. (Does not include radiative heating of evaporator.)

Conclusions

- UEDGE achieves 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.
- Integrated modeling, design, & experiments are needed.

Back-up Slides

A Simplified Lithium Vapor Box Divertor Based on UEDGE Results

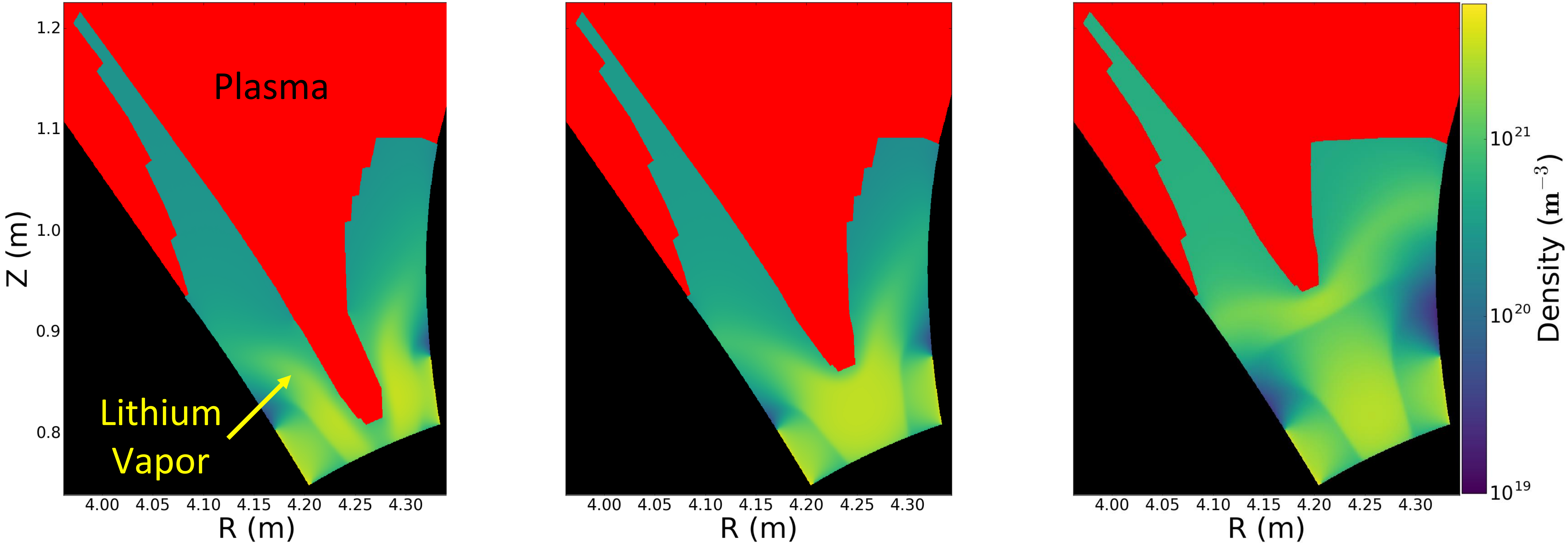


Allows more Li efflux, but needs less total evaporation
Makes experimental implementation easier, including starting with a toroidal segment

High Wall Temperatures Prevent Lithium Accumulation on First Wall

- 140 g/s of lithium evaporated for P_{rad} = 66 MW.
- Assume all of this is deposited on first wall, T_w ~ 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.

Two-Sided Injection Has Low Resilience



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

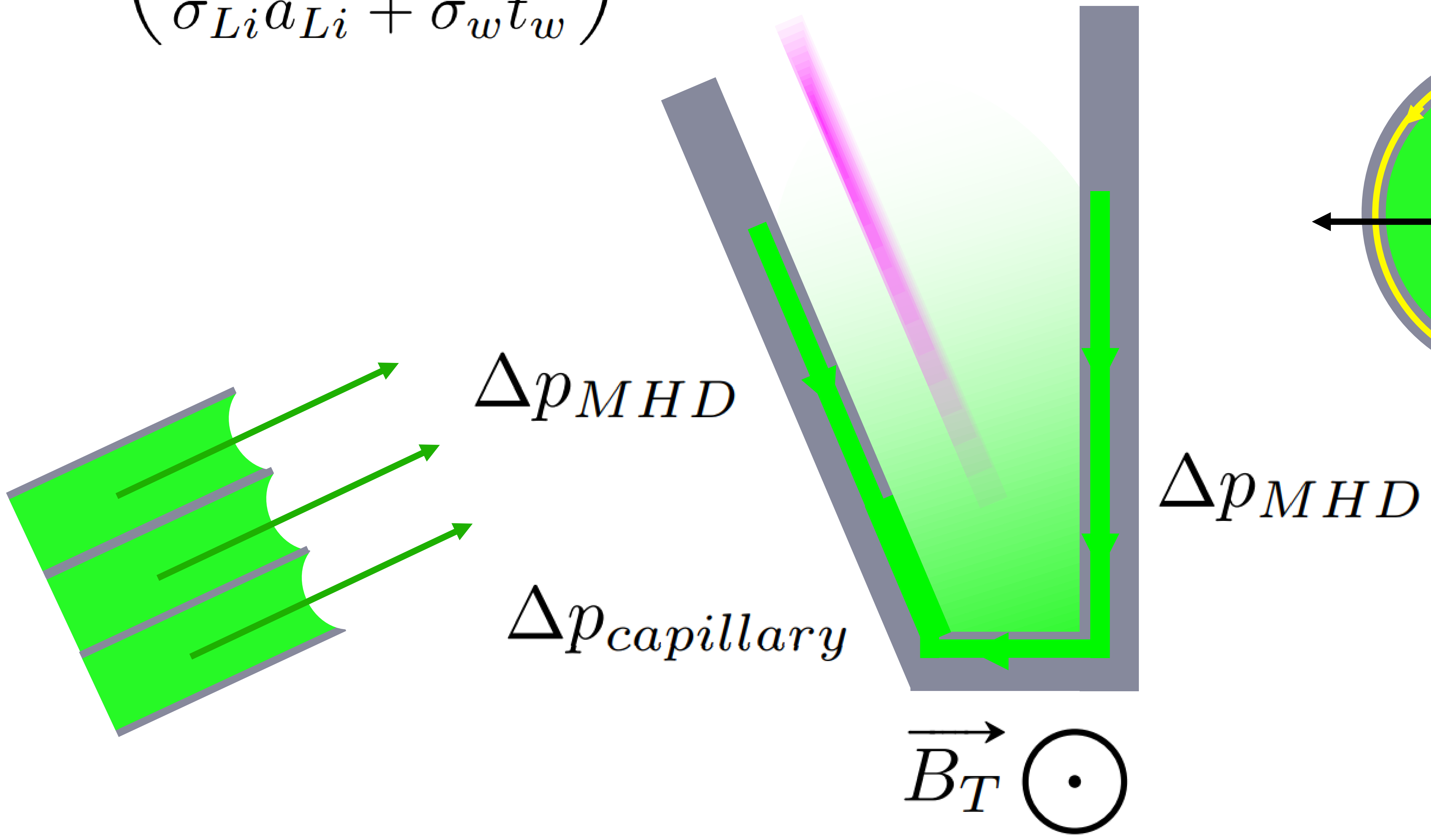
Lithium Return Flow is Determined by Balance between Capillary Pull & MHD Drag

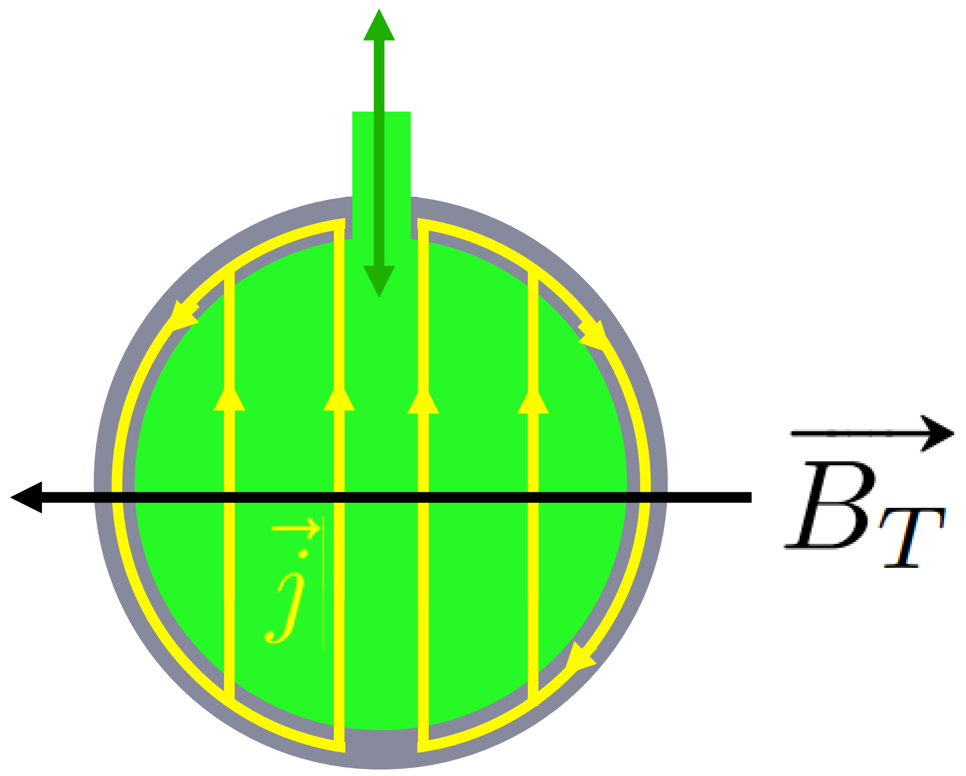
$$\Delta p_{capillary} = \frac{2\gamma \cos\alpha}{r_p} \geq \Delta p_{MHD}$$

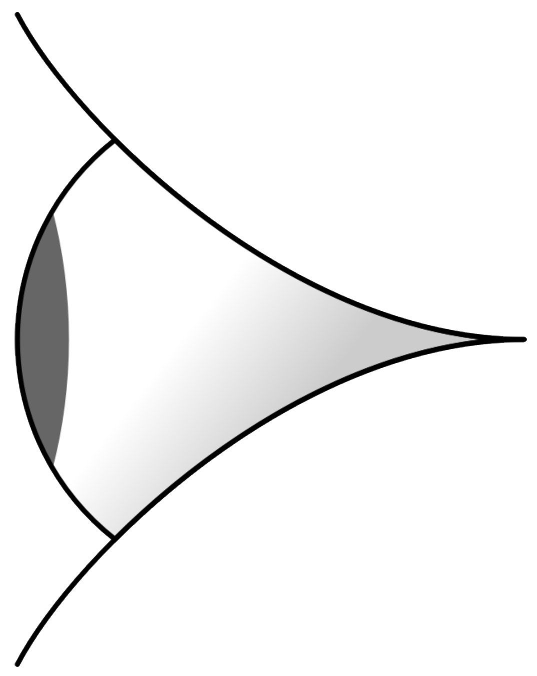
$$a_{Li} = \text{pipe radius}$$
$$t_w = \text{wall thickness}$$

$$\Delta p_{MHD} = \int \vec{j} \times \vec{B} \cdot \vec{dl} = \int v \sigma_{Li} B^2 dl \left(\frac{\sigma_w t_w}{\sigma_{Li} a_{Li} + \sigma_w t_w} \right)$$

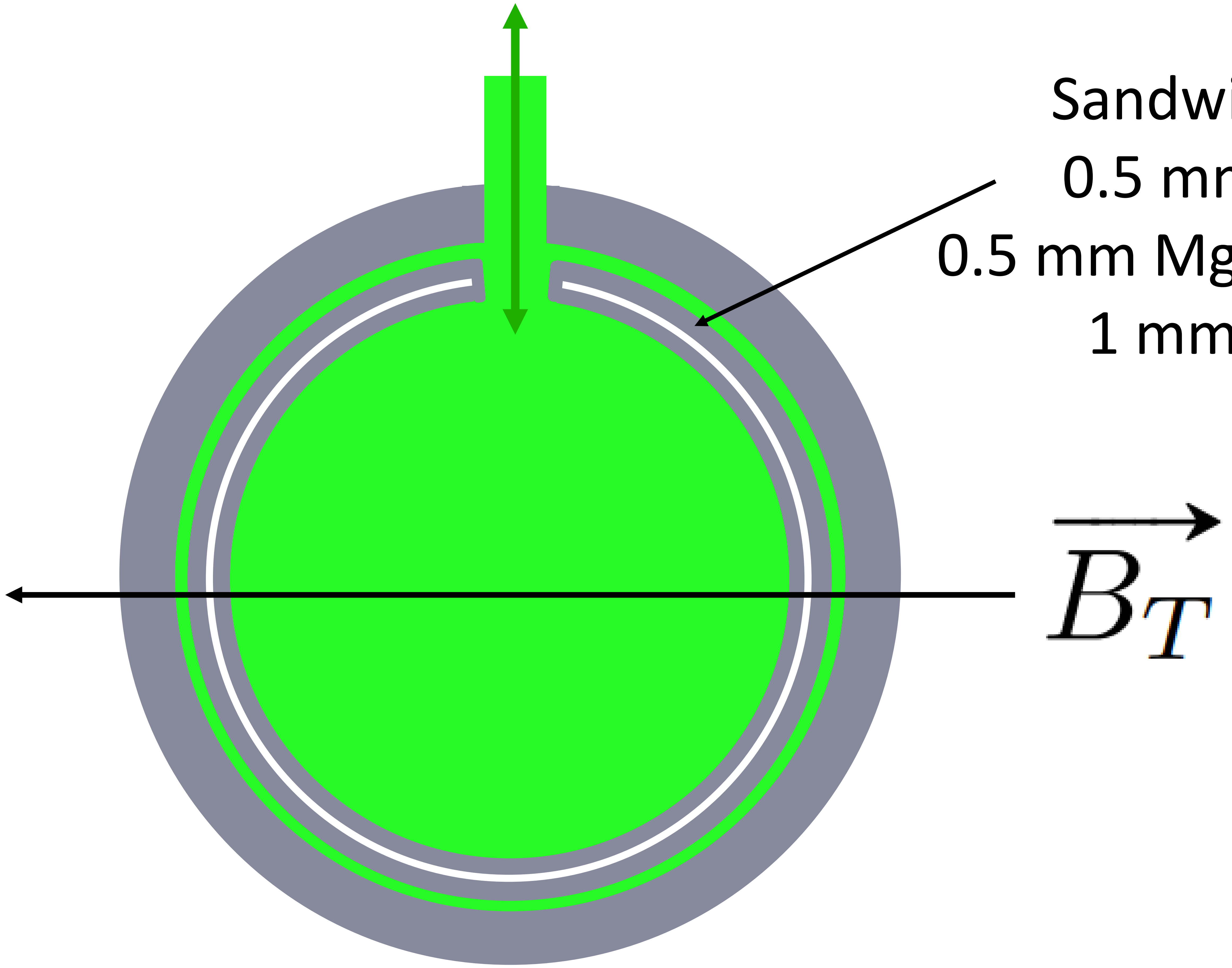
$$\gamma \equiv \textit{surface tension}$$
$$\alpha \equiv \textit{contact angle}$$
$$r_p \equiv \textit{pore radius}$$







Sandwich Flow Channel Inserts Reduce ΔP_{MHD}



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

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

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

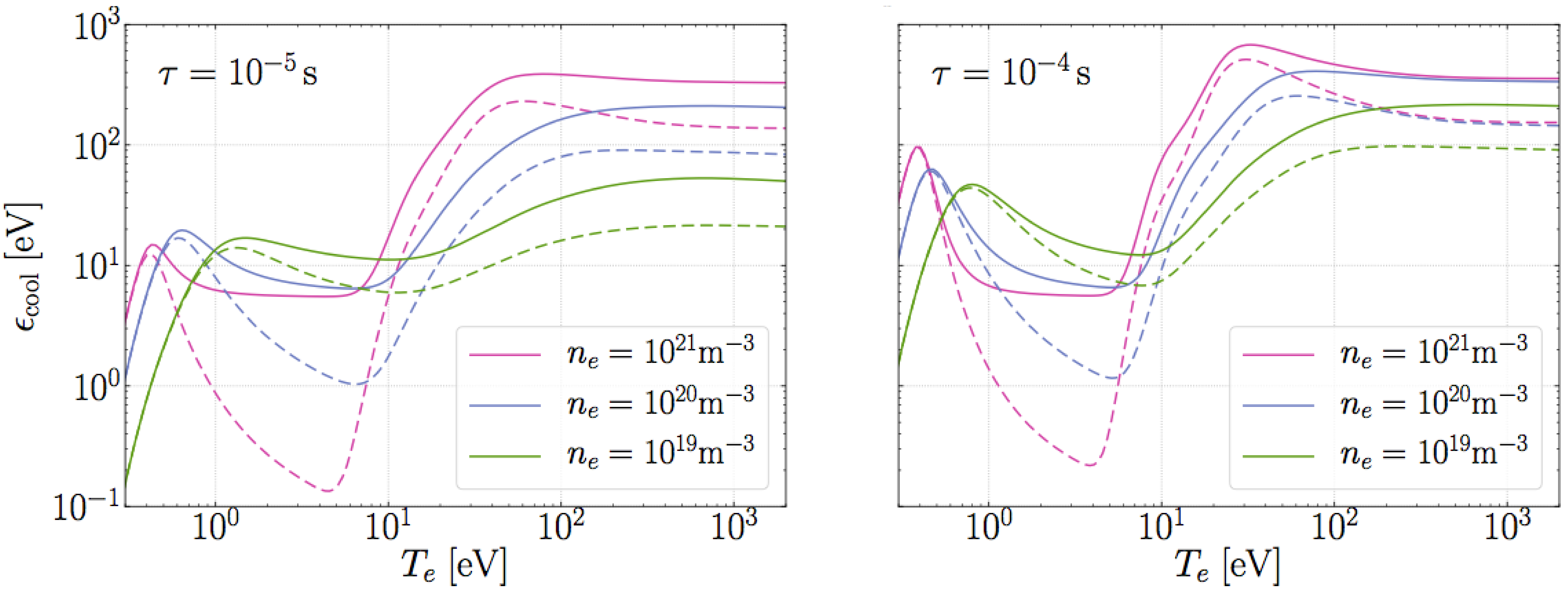
$@\,r_p = 40\,\mu m$

$v \leq 2.9\;mm/s$

$\phi = 0.4\,mV$

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

Expected Lithium Cooling per Particle

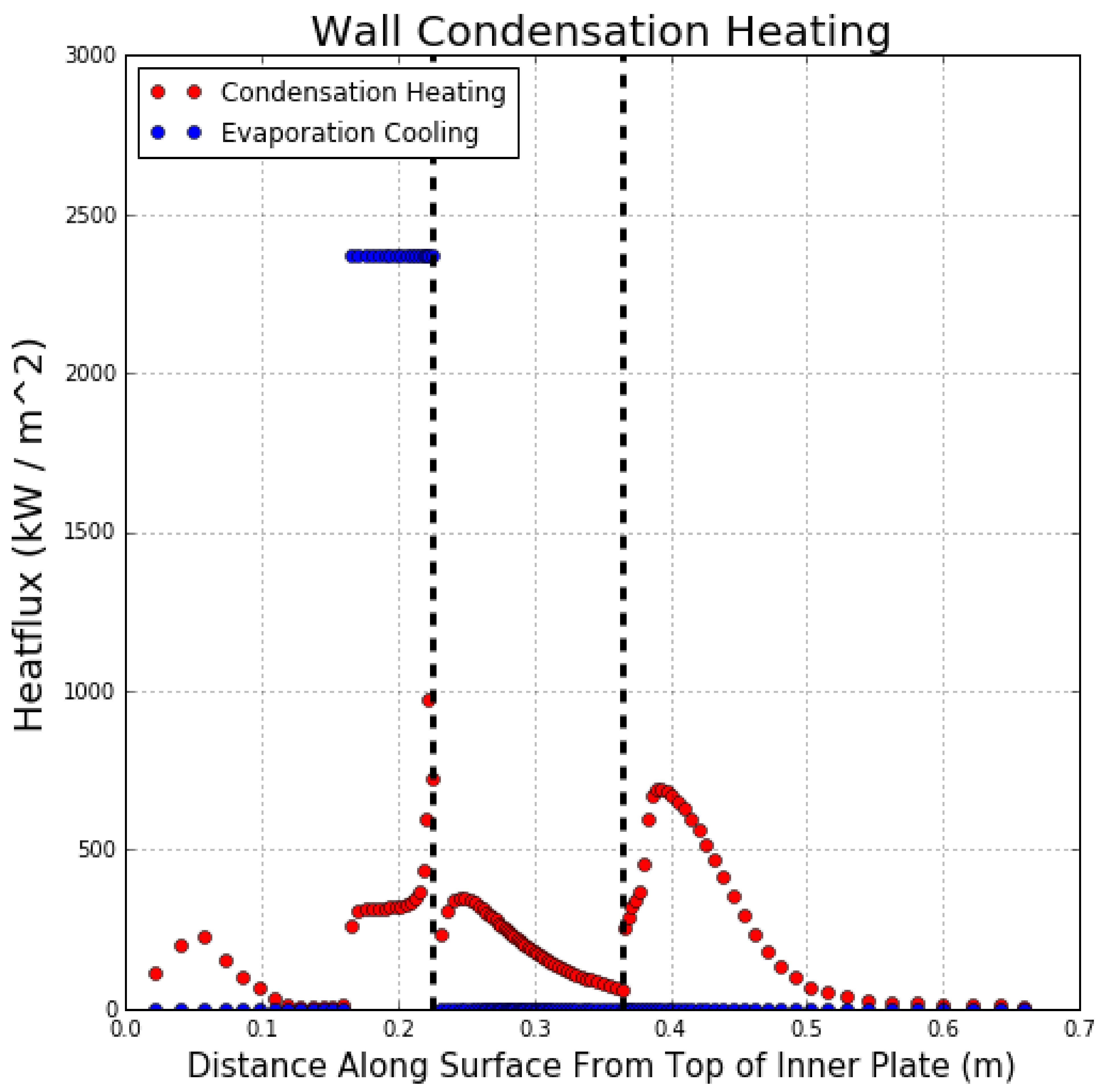


(Solid lines total cooling, dashed radiation only)

Simple model for power dissipation

based on ADAS Collisional-Radiative model

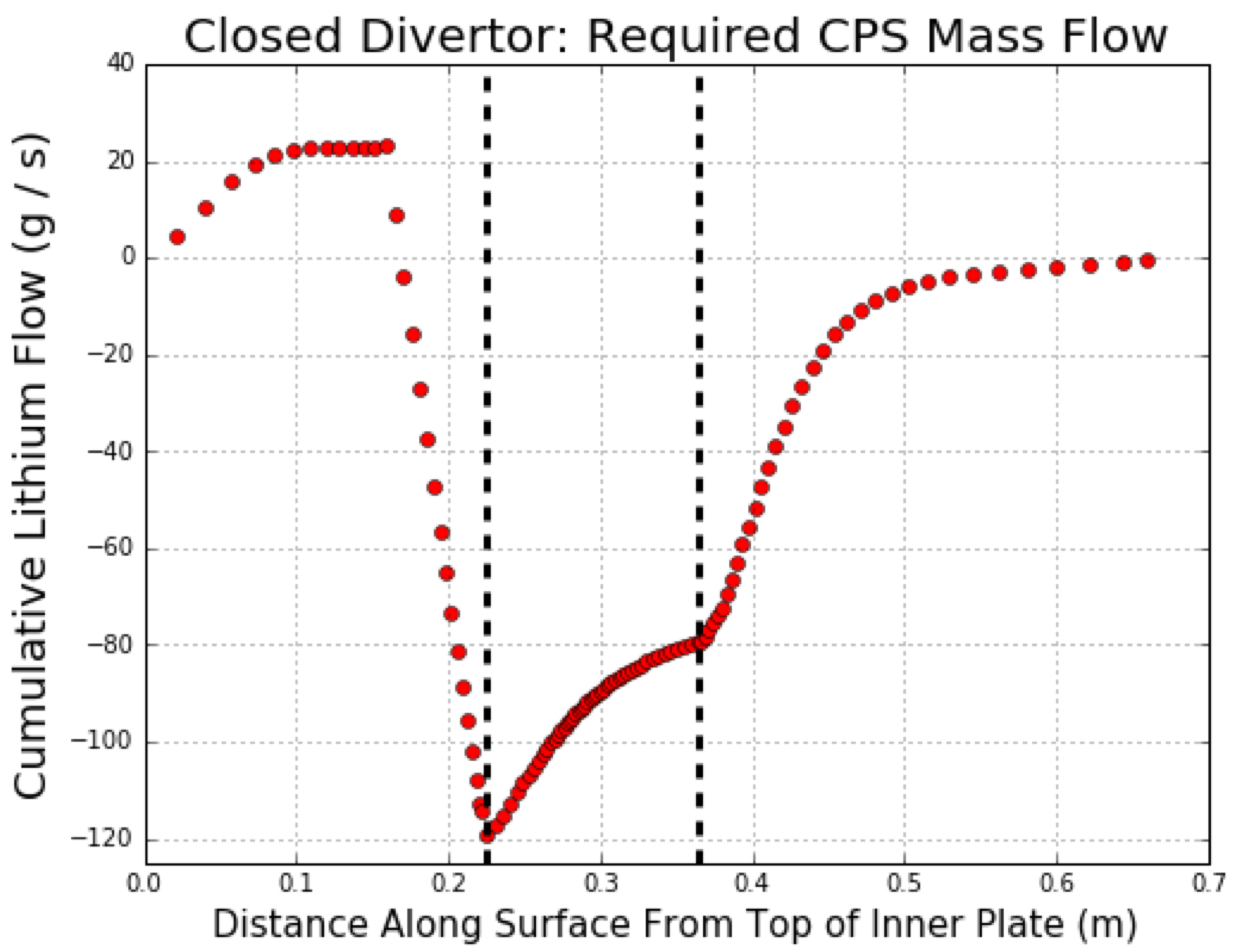
Evaporative Cooling & Heating

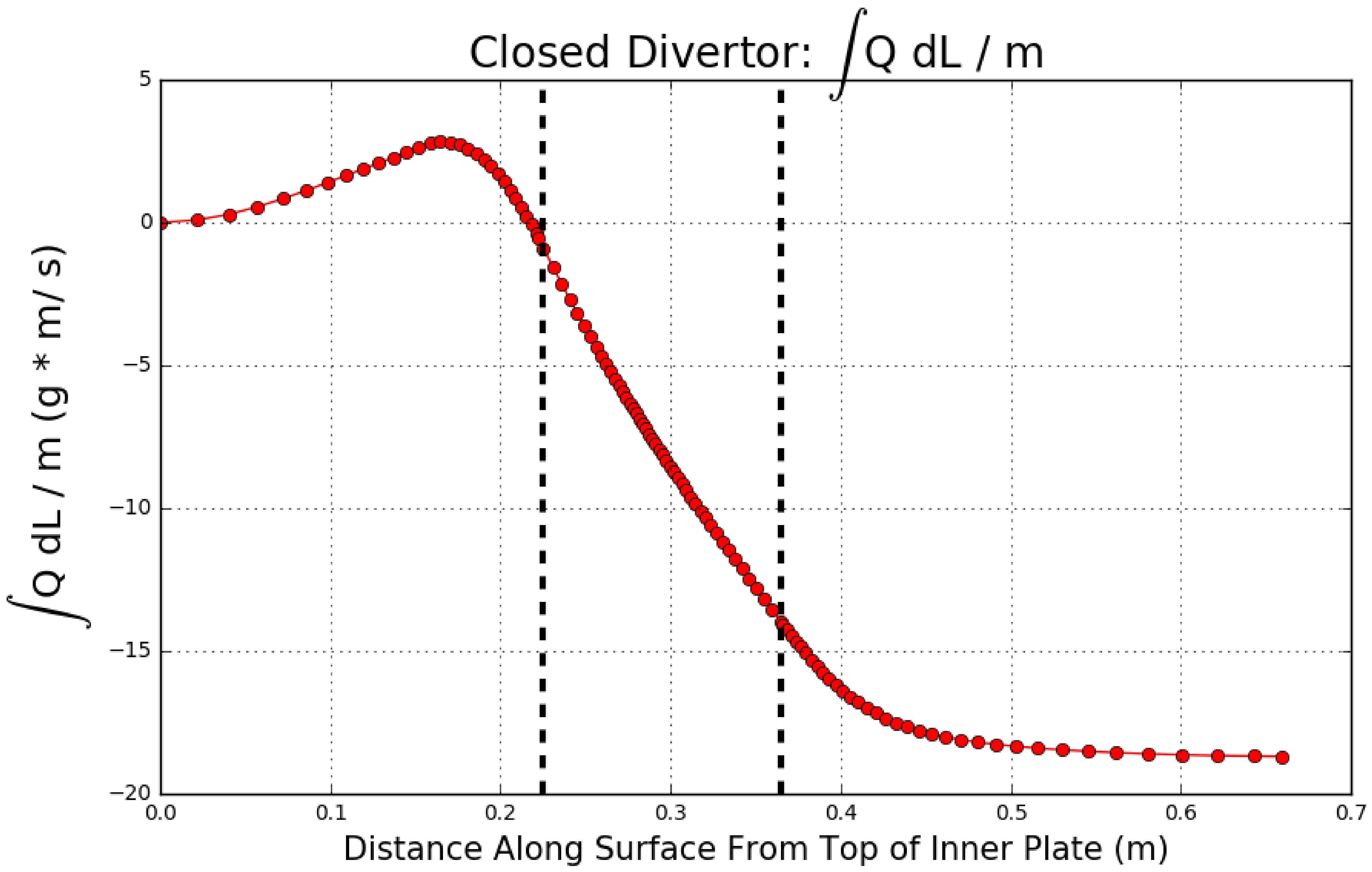


UEDGE heat flux to chamber walls is about 2 MW/m^2 all Li radiation

Divertor leg moving in front of evaporator should enhance evaporation, positional resilience.

Mass Flows


Closed Divertor: Required CPS Mass Flow
Cumulative Lithium Flow (g / s)
40
20
0
−20
−40
−60
−80
−100
−120
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Distance Along Surface From Top of Inner Plate (m)


Closed Divertor: ∫Q dL / m
∫Q dL / m (g * m/ s)
5
0
−5
−10
−15
−20
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Distance Along Surface From Top of Inner Plate (m)

Storing an image