Lithium Vapor-Box Diverter

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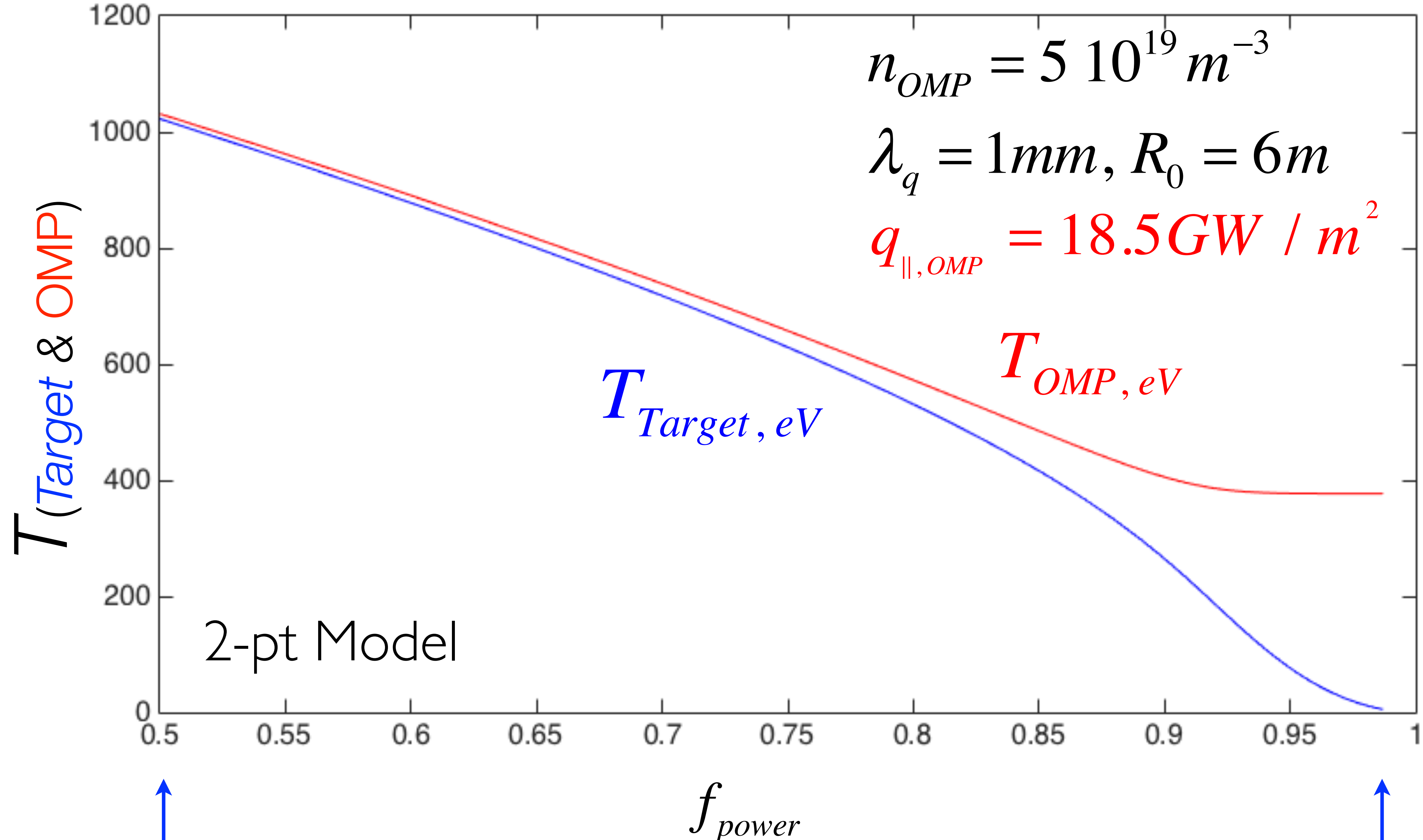
PPPL

Demo Needs Very High Dissipated Power

(Transport, Radiation, CX)

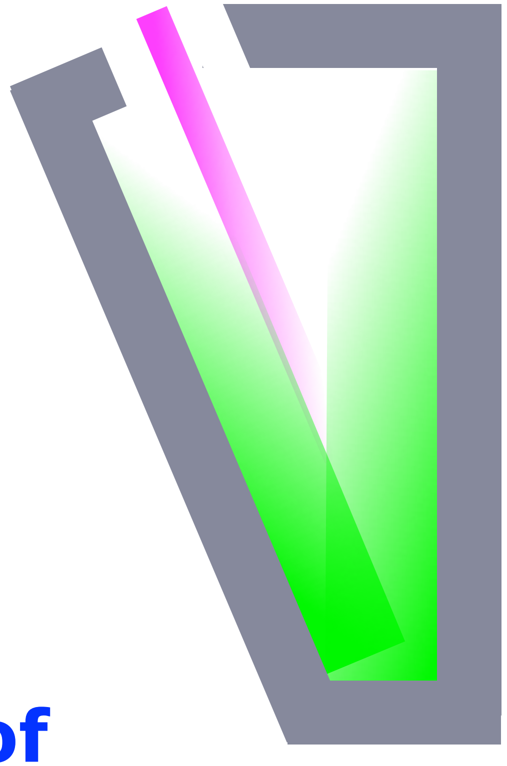


$p_{OMP} =$ $6300 Pa$

$q_{\perp,Target} = 300 MW/m^2$

$q_{\perp,Target} = 10 MW/m^2$

Pressure Balance with Lithium Vapor

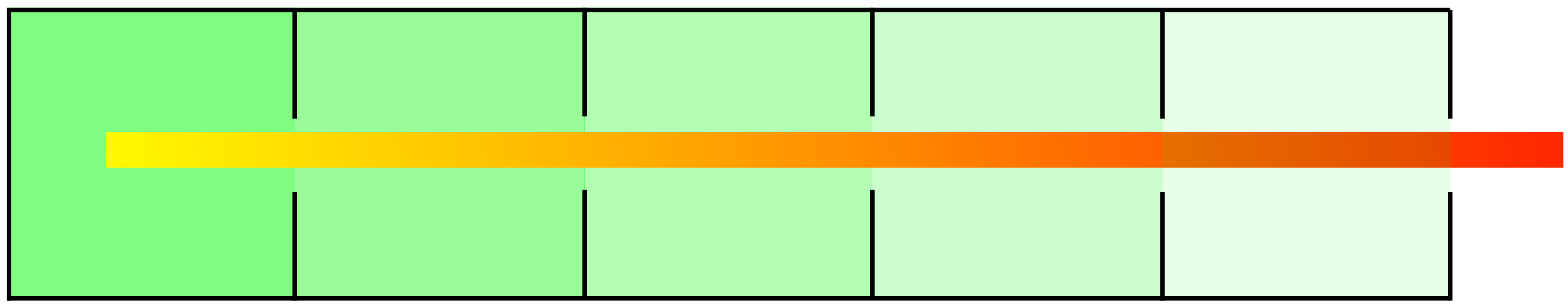


- Pressure balance achieved by many factors
  - C-X and elastic collisions with H^0
  - Recombination at very low T, high n
  - Elastic collisions with Li vapor
- Start with very conservative approach: ~1/2 of upstream pressure is balanced by Li vapor pressure (Jaworski, PSI 2014)
  - Why 1/2? $\lambda_{int} \sim \lambda_q + 1.64\, S \sim 2\, \lambda_q$
- Vapor must be well confined to divertor chamber.
  - Much easier with a condensing vapor than a gas.

Differentially Pumped Li Vapor-Box Divertor

End box

Main chamber →



T (wall) °C	950	787.5	625	462.5	300

- **Assume walls are coated with capillary porous material, soaked with liquid lithium, continually replenished.**
- **Assume each vapor box is well-mixed, at local *n_{vap}* and *T_{vap}***
- **Assume Langmuir-like evaporation / condensation at walls**

$$\Gamma_{Li}\ (\text{to wall}) = n_{vap}\sqrt{\frac{kT_{vap}}{2\pi m}} - n_{eq}\left(T_{wall}\right)\sqrt{\frac{kT_{wall}}{2\pi m}}$$

- **Assume ideal-gas choked nozzle flow through apertures**

$$\Gamma_{Li}\ (\text{thru nozzle}) = 0.6288 \cdot n_{vap}\sqrt{\frac{kT_{vap}}{m}}$$

Particle and Power Balance

- **Time-independent densities (particle balance)**

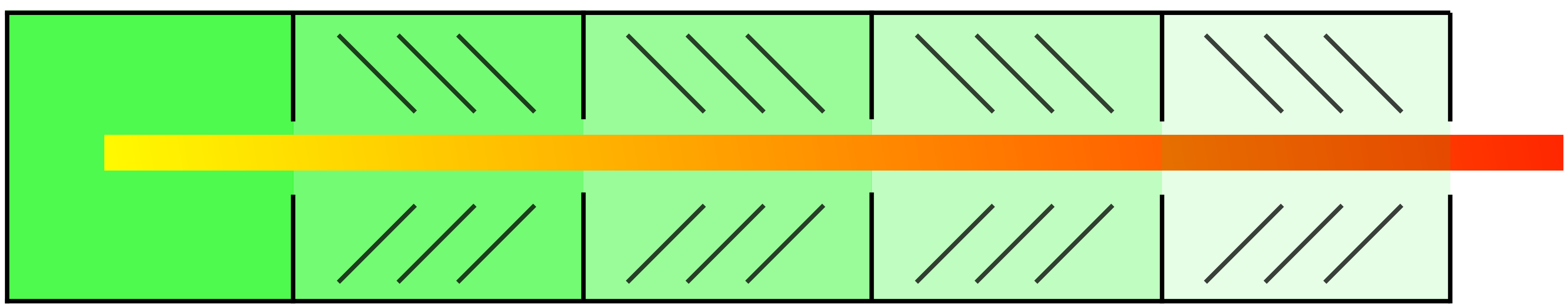
$$0.6288\left(A_{noz,i-1}n_{i-1}\sqrt{kT_{vap,i-1}/m}-A_{noz,i}n_{i}\sqrt{kT_{vap,i}/m}\right)$$
$$+\sqrt{\frac{k}{2\pi m}}A_{wall,i}\left[n_{eq}\left(T_{wall,i}\right)\sqrt{T_{wall,i}}-n_{i}\sqrt{T_{vap,i}}\right]=0$$

- **Time-independent temperatures (enthalpy balance)**

$$0.6288\left(\frac{5}{2}kT_{vap,i-1}A_{noz,i-1}n_{i-1}\sqrt{kT_{vap,i-1}/m}-\frac{5}{2}kT_{vap,i}A_{noz,i}n_{i}\sqrt{kT_{vap,i}/m}\right)$$
$$+\sqrt{\frac{k}{2\pi m}}A_{wall,i}\left[\frac{5}{2}kT_{wall,i}n_{eq}\left(T_{wall,i}\right)\sqrt{T_{wall,i}}-\frac{5}{2}kT_{vap,i}n_{i}\sqrt{T_{vap,i}}\right]=0$$

- **Two equations for two unknowns for box *i* in terms of box *i* - 1 (due to supersonic flow in choked nozzles).**

Solution without Plasma

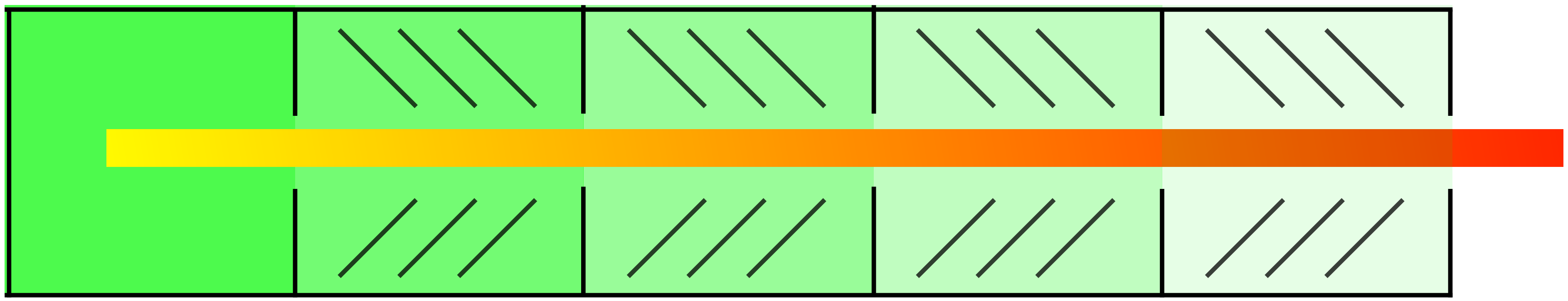


T (wall) (C)	950	787.5	625	462.5	300
T (vapor) (C)	950	866	820	812	812
n (vapor) (m^{-3})	1.51e23	3.25e22	4.17e21	4.33e20	4.38e19
Mass flow (kg/s)	4.98	1.04	0.131	0.0135	0.00137

- **Vapor boxen are 0.4m x 0.4m, R_0 = 6m**
- **Apertures are 0.1m**
- **Initial numerical calculations indicate need for reflecting surfaces to stimulate mixing (Hakim & Hammett)**

Entrain Lithium Flux to Plasma Sheet and Eject with 200 MW into Bottom Box

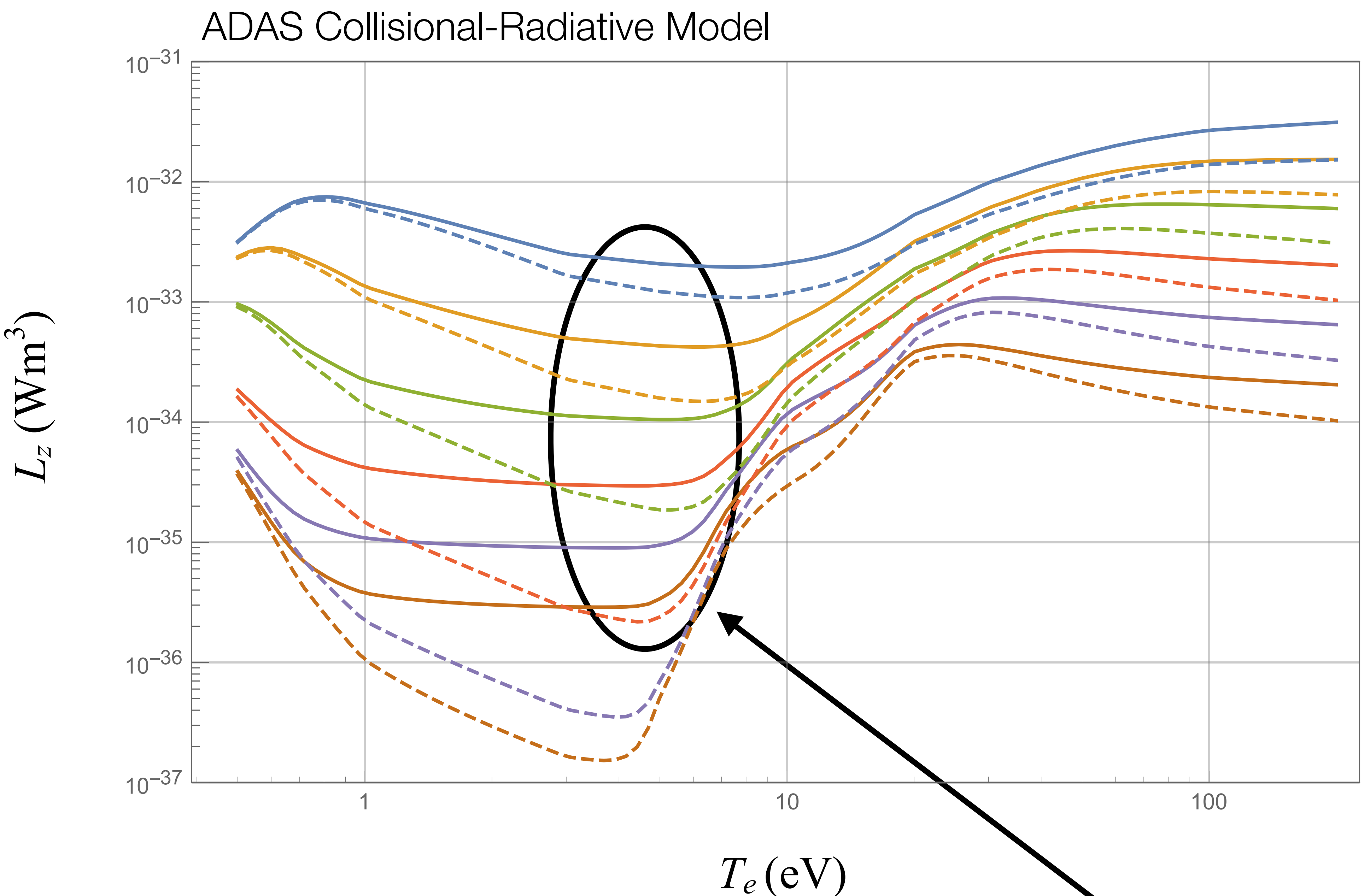
As if all plasma heat were invested in ionization of lithium, and all recombination happened in bottom box.



T (wall) (C)	950	787.5	625	462.5	300
T (vapor) (C)	2443.9	1756.5	1533.9	1499.1	1498.6
n (vapor) (m^{-3})	1.15E+23	1.80E+22	1.74E+21	1.23E+20	8.21E+18
Mass flow (kg/s)	5.3605	0.7124	0.0643	0.0045	0.00037
Latent heat flow (W)	1.05E+08	1.40E+07	1.26E+06	8.81E+04	5.89E+03
Enthalpy flow (W)	3.92E+07	3.75E+06	2.95E+05	2.02E+04	1.35E+03
Wall heat flux (W/m^2)	9.85E+05	2.40E+06	3.06E+05	2.74E+04	1.91E+03

Note: NSTX thrives on 0.22g/sec from dropper

Conservative ΔE_{cool}/ptcl. for Lithium



$\tau_z = 100\mu\sec$

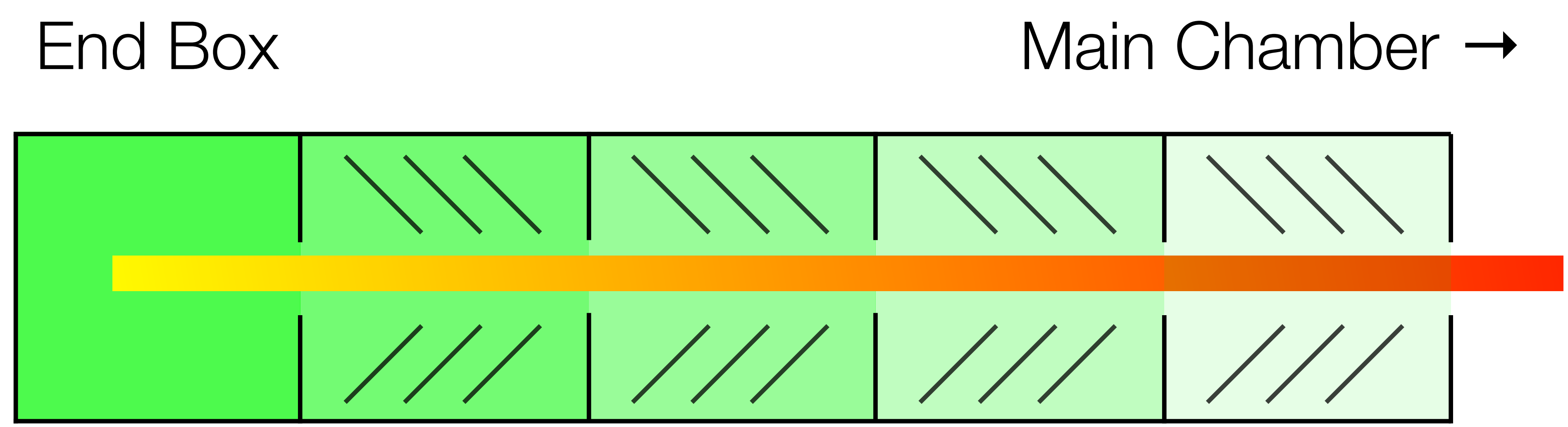
$n_z = \tau_z S / V$

Solid lines: total cooling
Dashed: radiation only

$$\left.\frac{\Delta E}{ptcl.}\right|_{cool} = \frac{p_{cool}V}{S} = \frac{n_e n_z L_Z V}{S} = n_e \tau_z L_Z \sim 6.2eV/ptcl.\ \ (L_z/n_e\tau_z \sim const.)$$

Radiated Power @ 10 eV / Atom Injected

(using solution above)



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n (vapor) (m^{-3})	1.15E+23	1.80E+22	1.74E+21	1.23E+20	8.21E+18
Radiated Power (W)		5.36E+08	4.89E+07	3.42E+06	2.29E+05

- **Previous solution was very conservative, assuming upstream pressure balanced against Li vapor pressure.**
- **Now considering that 100% radiated power implies recombination; H^0 + Li^0 flow balances upstream pressure.**
- **Might not need the end 2 boxes; makes problem easier.**

To Do List

- Proper fluid mechanics calculations
    - Now started by Hakim and Hammett
- Proper plasma calculations.
    - Thermal force? Flow reversal in outer layers?
    - Self consistent combination with fluid solution.
- Concept for how to recirculate the lithium.
    - Can we use passive or active heat-pipe technology?
    - How to recover lithium that escapes?
- Design and testing of a water/steam - based prototype?
- Design and testing of a lithium-based prototype.
- Add plasma in a test stand?
- Install in a tokamak.

Foundational Work

Energy Exhaust through Neutrals in a Tokamak Divertor
M.L. Watkins and P.H. Rebut, 19th EPS Conf., Innsbruck, 1992, vol. 2, p. 731.

Liquid Lithium Divertor System for Fusion Reactor
Y. Nagayama et al., Fusion Eng. Des. **84** (2009) 1380

Recent Progress in the NSTX/NSTX-U Lithium Program and Prospects for Reactor-Relevant Liquid-Lithium Based Divertor Development
M. Ono, M.A. Jaworski, R. Kaita et al., Nuc. Fusion **53** (2013) 113030

Liquid-Metal Plasma-Facing Component Research on NSTX
M. Jaworski, A. Khodak and R. Kaita, *Plasma Phys. Control. Fusion* **55** (2013) 124040