

Debris Generation and Balance in a Li EUV Source

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Outline

- **Motivation**
 - Advantages of lithium
 - Protective Li surface layer
- **Model for lithium steady-state layer**
 - Assumptions
 - Calculations of Li fluxes
- **Optics degradation implications**
- **Conclusion**



Motivation

- Advanced fuels like Li and Sn can achieve higher conversion efficiencies than Xe!
- However, Sn & Li can produce high energy debris and condense/coat surfaces.
- High energy ions erode and damage optics, severely impacting lifetime and CoO.
- Li/Sn vapor can coat mirror surfaces and degrade reflectivity before mirror erosion is appreciable.
- Plasma cleaning may be able to remove deposited debris and achieve a steady-state balance to work in concert with lifetime extension!

Xe

- Main UTA at 11 nm
- Secondary UTA at 13.5 nm
- Fewer states emit
- Conversion efficiency is limited to $\sim < 1\%$

Sn

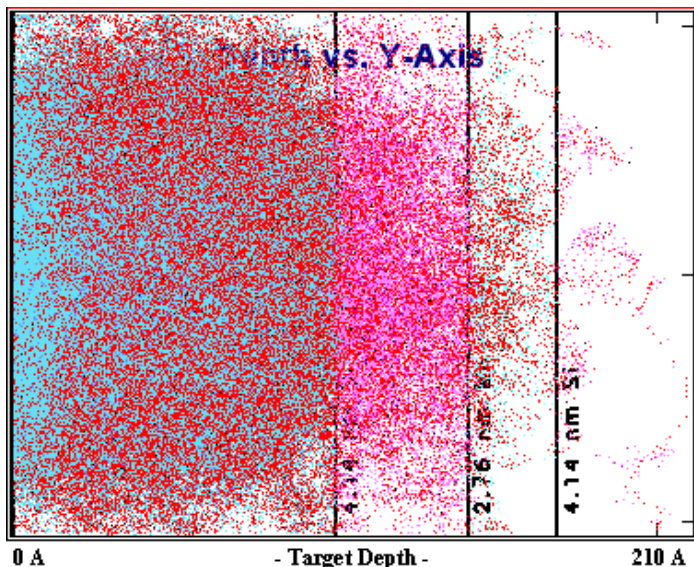
- Main UTA shifts to 13.5 nm
- Many states emit

Li

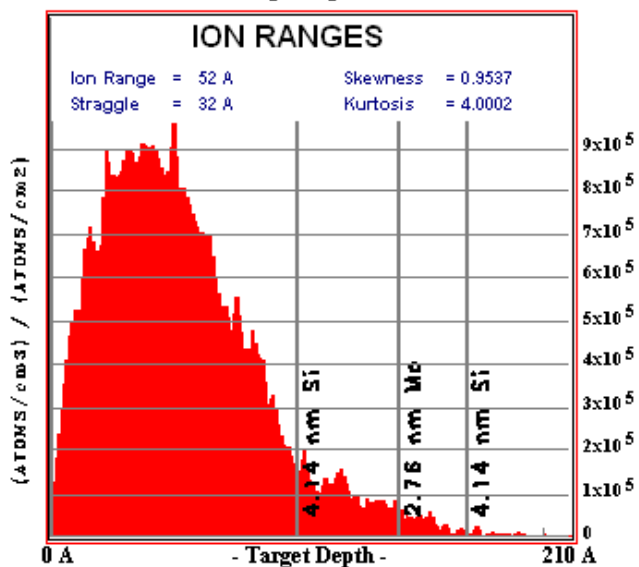
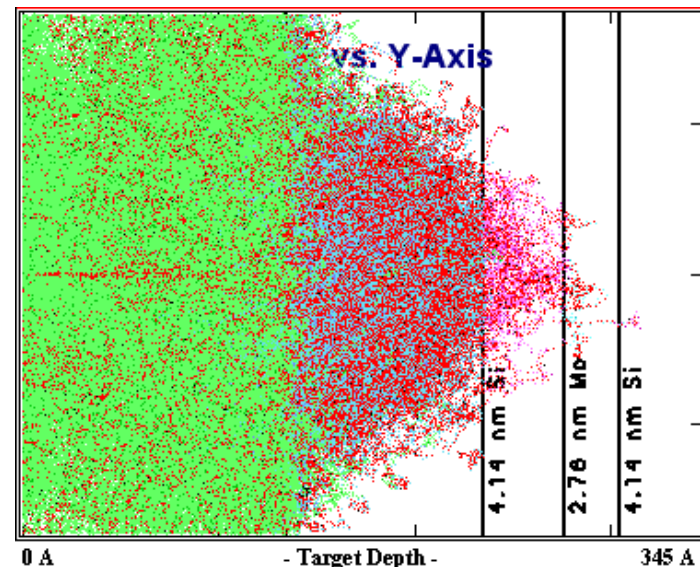
- Transition in Li^{2+} emits at 13.5 nm
- Low charge state and low mass, high vapor pressure

CE of $\sim 3\%$

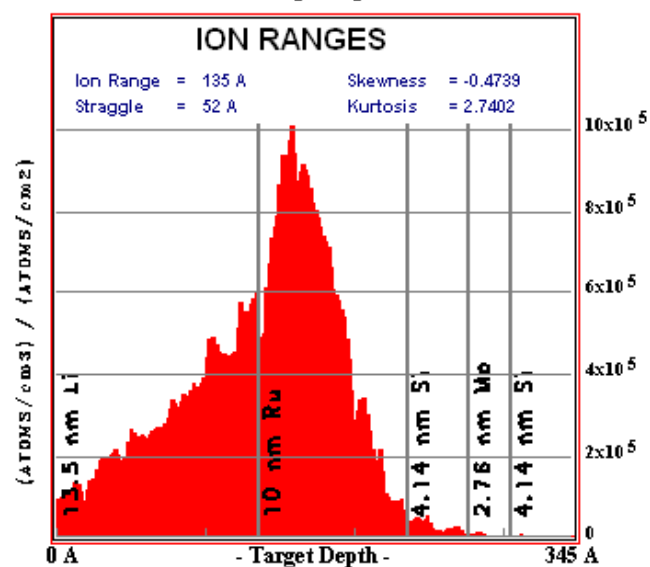
Li Ion Range Comparison



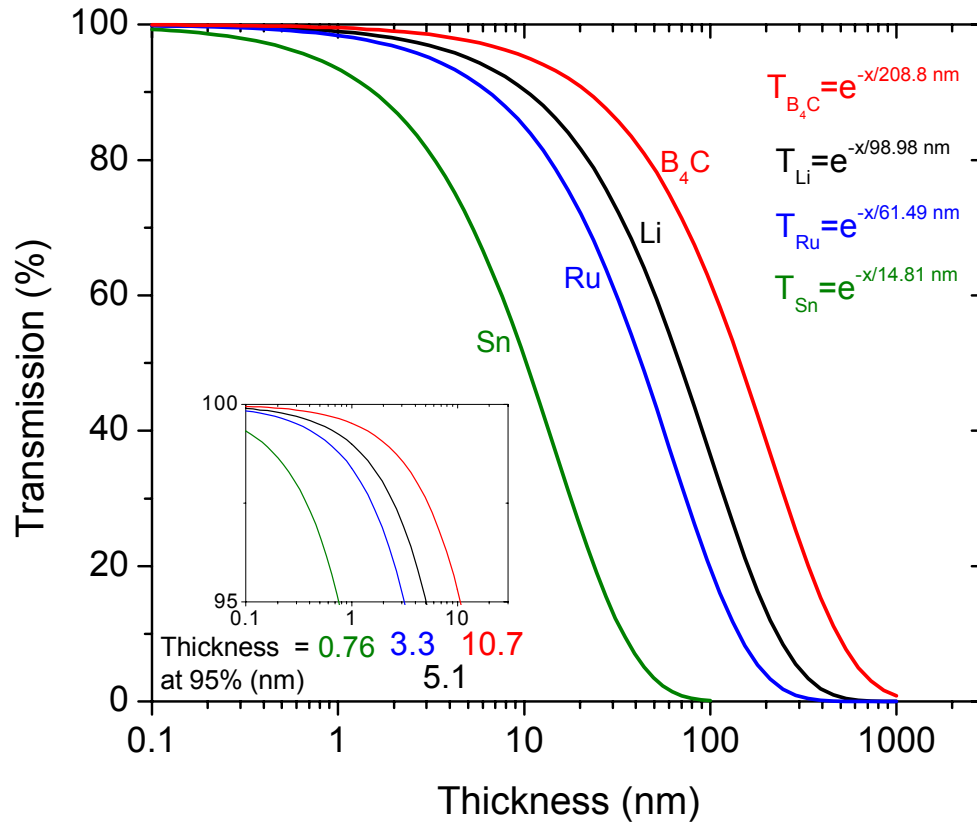
←
Bare Ru-
capped
MLM



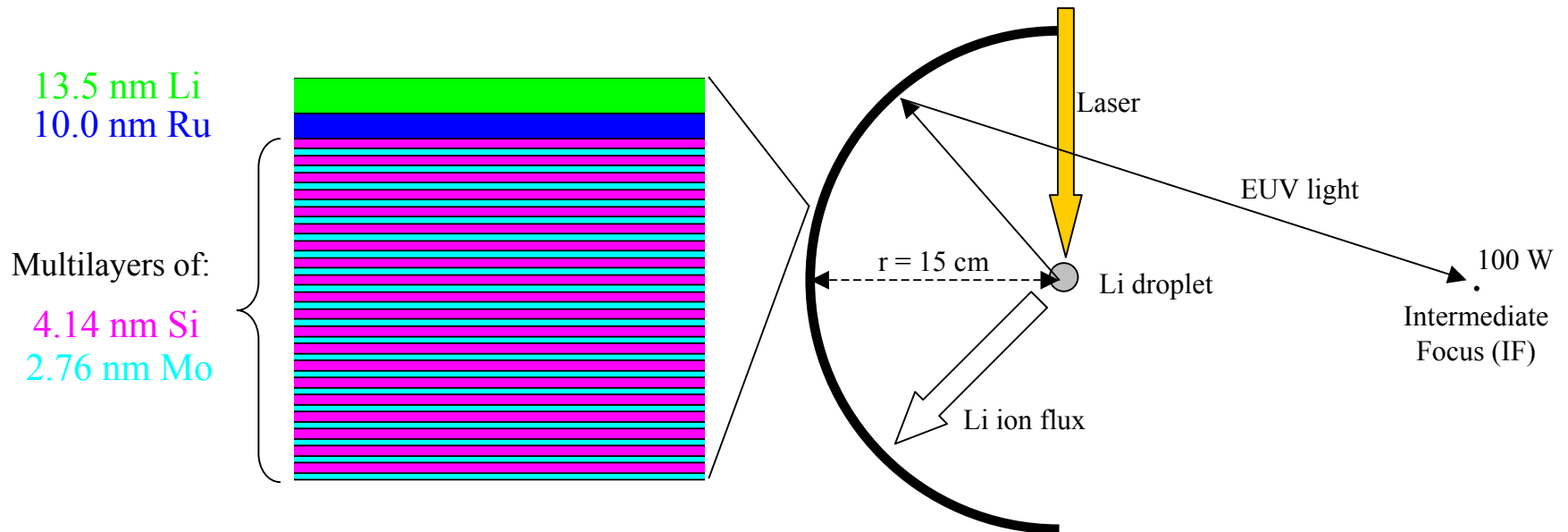
With
Li
layer
→



Transmission of EUV Through Layers



Device Geometry



- **Collects 2π steradians (1/2 of light emitted)**
- **Mirror surface area = 0.14 m^2**
- **Reflectivity = 65%**

Laser-Produced Plasma Assumptions

- Operated at a repetition rate of 10 kHz
- Laser pulse length of 2 ns
- Lithium plasma:
 - Local thermodynamic equilibrium (LTE)
 - Electron density of 10^{26} m^{-3}
- Fast Li debris ions, $E = 1 \text{ keV}$

Local Thermodynamic Equilibrium

- $T_e = T_i$
- **Saha-Boltzmann equilibrium**
 - Ionization states – Saha Equation

$$\frac{N_{i+1}}{N_i} = \frac{2Q_{i+1}}{n_e Q_i} \left(\frac{2\pi m_e kT}{h^2} \right)^{\frac{3}{2}} \exp\left[\frac{-\chi_{i \rightarrow i+1}}{kT} \right]$$

- Partition function, Q

$$Q_i = \sum_{p \in \text{all states}} g_p \exp\left[\frac{-E_p}{kT} \right]$$

- Excitation states – Boltzmann Equation

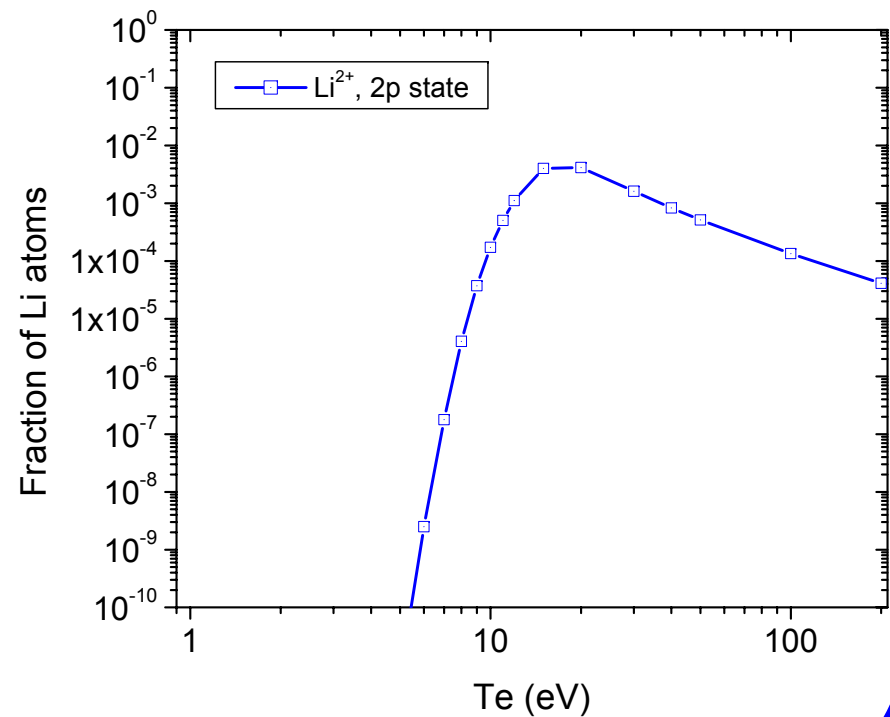
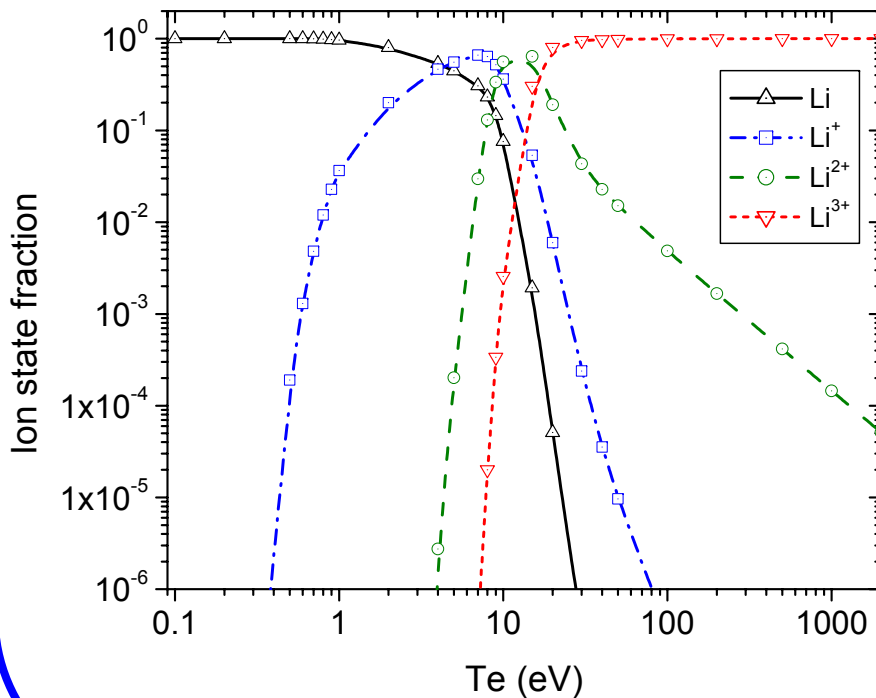
$$\frac{N_B}{N_A} = \frac{g_B}{g_A} \exp\left[\frac{-(E_B - E_A)}{kT} \right]$$

Results of LTE Analysis

Ionization states of lithium vs. temperature

Fractional population of the 2p excited state of Li^{2+}

0.0039 @ 15 eV



Photons Required Per Shot

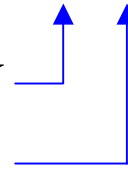
- Want 100 W of 13.5 nm light at IF
- To get 400 W from plasma:

$$P_{\lambda=13.5 \text{ nm}} = 400 \text{ W} = N_{\gamma} E_{\gamma} f$$

Photon energy = 91.8 eV

Repetition rate = 10 kHz

→ 2.7×10^{15} photons/shot



Amount of Lithium Required

- To get 2.7×10^{15} photons per shot:

$$N_{\gamma} = 2.7 \times 10^{15} = N_{\text{Li}} \frac{N_{\text{Li}^{2+}, 2p}}{N_{\text{Li}}} A t_{\text{pulse}}$$

Fraction in $2p$ state = 0.0039

Transition probability = $3.04 \times 10^{11} \text{ s}^{-1}$

Pulse time = 2 ns

→ Number of Li atoms = 1.2×10^{15} → droplet $r = 18$ microns

Power Balance Can Determine Absolute # of Fast Li Ions

To get 400 W of 13.5 nm light, with 2.5% efficiency
→ Laser input power = 16 kW

Assuming a fraction β goes into fast ions
→ (16β) kW to fast ions

Ions have 1 keV energy each

$$N_{\text{Li}^+} = \frac{P_{\text{Li}^+}}{E_{\text{Li}^+}}$$

→ There are $(\beta) \times 1.0 \times 10^{20} \text{ s}^{-1}$ fast ions generated

Lithium Deposition on Mirror

- **We have now:**
 - Lithium injected into machine = $1.16 \times 10^{19} \text{ s}^{-1}$
 - Lithium emerging as fast ions = $\beta \times 1.0 \times 10^{20} \text{ s}^{-1}$
 - note that $\beta < 0.116$
- **The remaining lithium sticks**
 - Assuming a mass-limited Li target, this means there are $(0.116 - \beta) \times 10^{20} \text{ s}^{-1}$ sticking
 - If it is not mass-limited, much more is available to stick.
- **Mirror surface area of 0.14 m^2**
- ➔ **At least a flux of $(0.83 - 7.1 \beta) \times 10^{20} \text{ m}^{-2}\text{s}^{-1}$ deposited on mirror**

Sputtering Data

- **VFTRIM-3D¹**

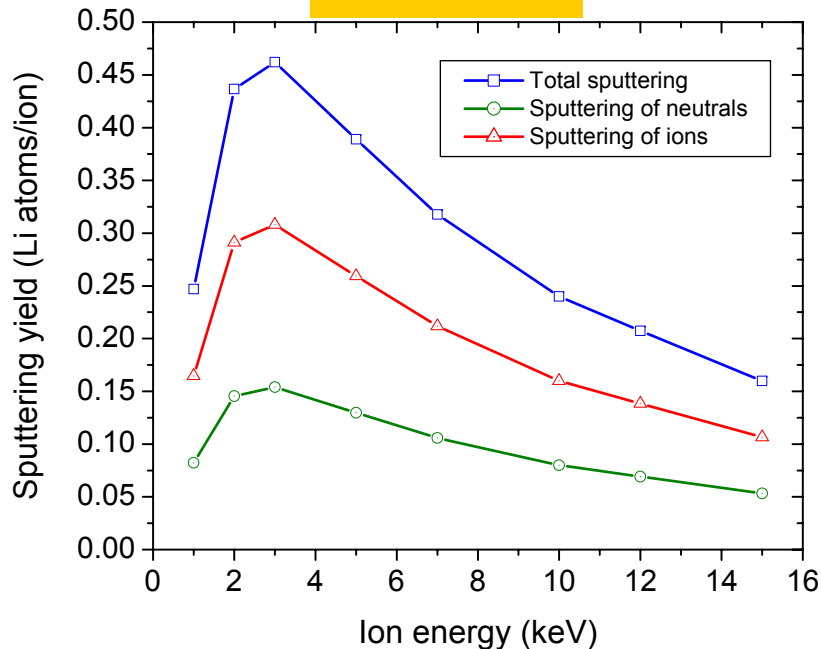
- A binary-collision approximation (BCA) simulation code
- Based on TRIM (Transport of Ions in Matter) with modifications for atomic-scale surface roughness using a fractal algorithm.

135 Å Li

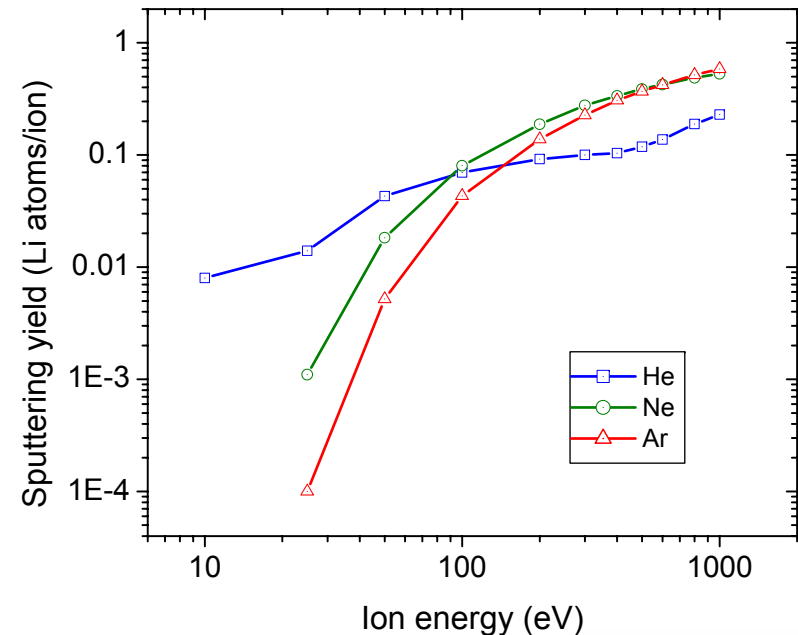
100 Å Ru

∞ 50/50 Si/Mo

Li⁺ on Li



He⁺, Ne⁺, Ar⁺ on Li



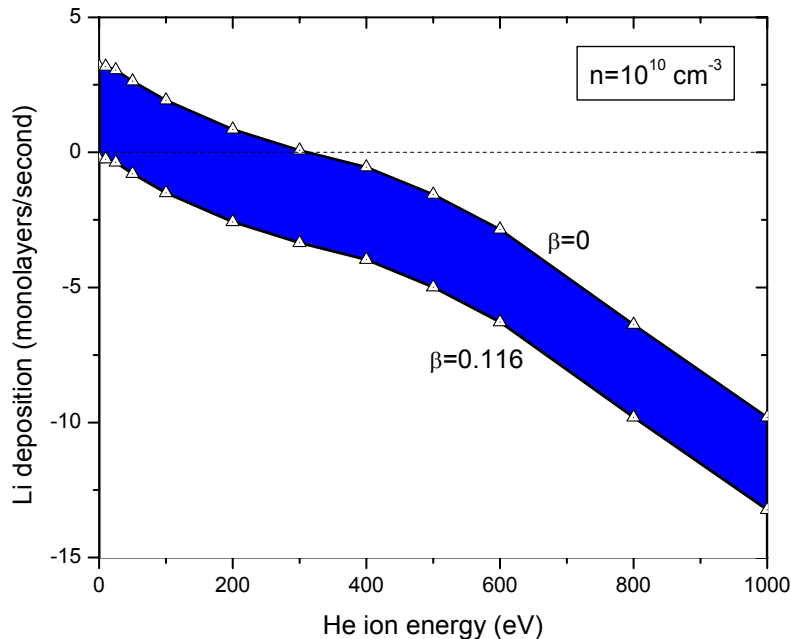
Erosion of Lithium Due to Li^+

- **Sputtering yield of 0.24 @ 1 keV**
 - **High energy Li will not sputter enough Li buildup**
- A secondary plasma is needed**

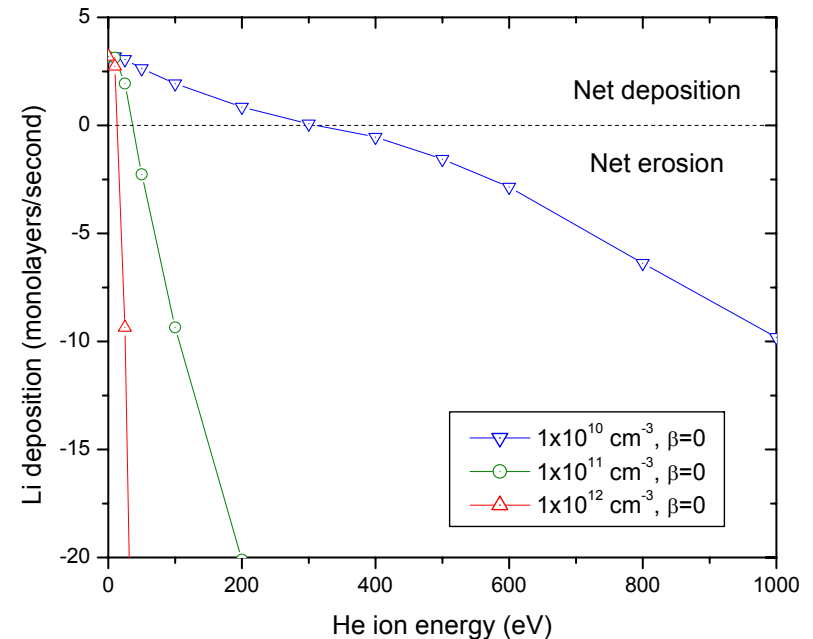


Helium Plasma Requirements

Moderate density plasma
Dependent on beta



“Worst-case” (in terms of Li buildup)
Varying density

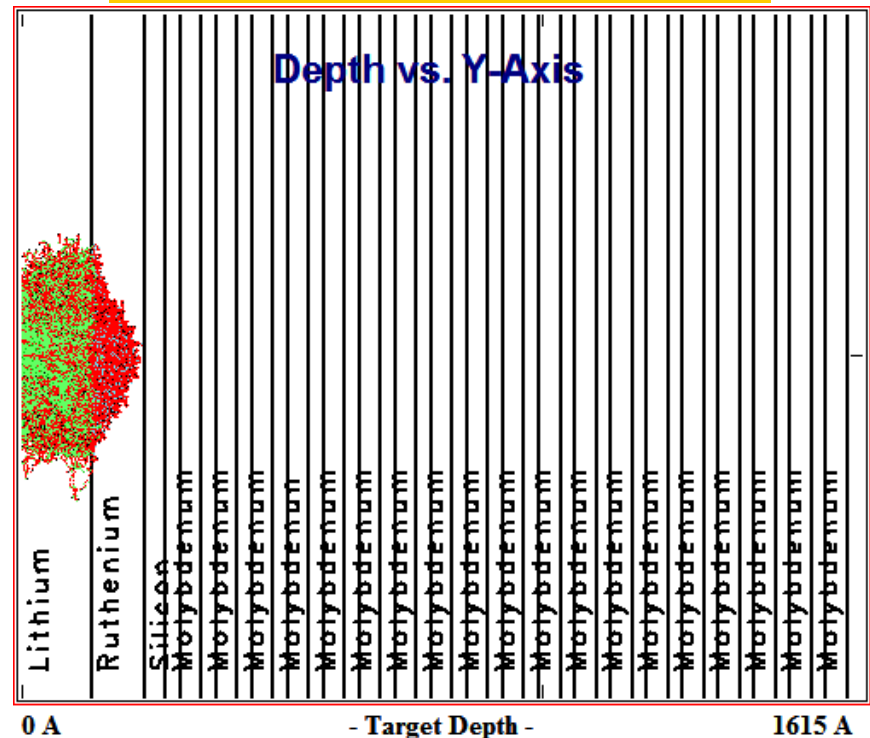


Mirror Damage Due to He Secondary Plasma

Stopping and Range of Ions in Matter (SRIM) code¹

→ He⁺ does not damage the Si/Mo layers

He⁺ on mirror at 300 eV
100,000 incident ions



¹J. F. Ziegler et al., *The Stopping and Range of Ions in Matter*. (Pergamon Press, New York, 1985).

Mirror Erosion

- **No sputtering of underlying Si & Mo layers in VFTRIM for 300 eV He⁺**
- **If a higher density plasma is used, He energy can be even lower and be below the sputtering threshold for Ru**
- **Sputtering of Li or Ru only for 1 keV Li, not for He, Ne, or Ar up to 1000 eV**

→ Erosion is not a problem due to He

Conclusions

- **A model developed to estimate:**
 - Distribution of ionization/excitation states of Li
 - Li fluxes to mirror
 - Li erosion/deposition balance
 - Mirror damage, lifetime
- **Results of model**
 - He plasma is needed – can remove Li debris for steady state
 - No erosion of Si & Mo layers
 - He plasma will not damage the mirror
 - Energetic Li⁺ ions cause damage
- **Revised assumptions or better input numbers are needed for accurate lifetime calculations**
 - Li fluxes would change
 - Model could be easily re-run

Acknowledgements

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