NSTX-U

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Erosion and re-deposition of lithium coatings on graphite and TZM molybdenum in support of NSTX-U divertor operations

Tyler Abrams

M.A. Jaworski, R. Kaita, D.P. Stotler, G. De Temmerman, M.A. van den Berg, H.J. van der Meiden, T.W. Morgan

and the NSTX-U Research Team

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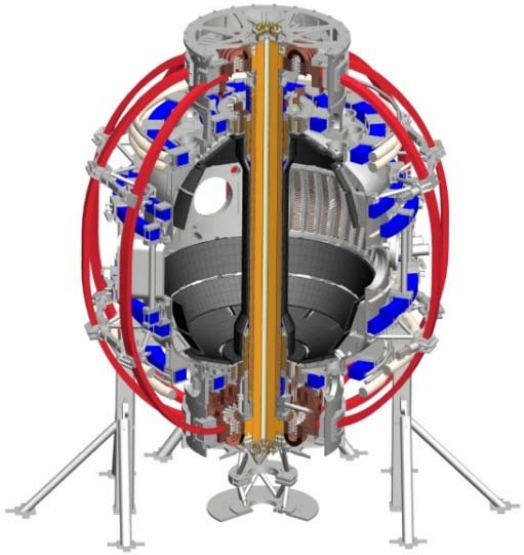
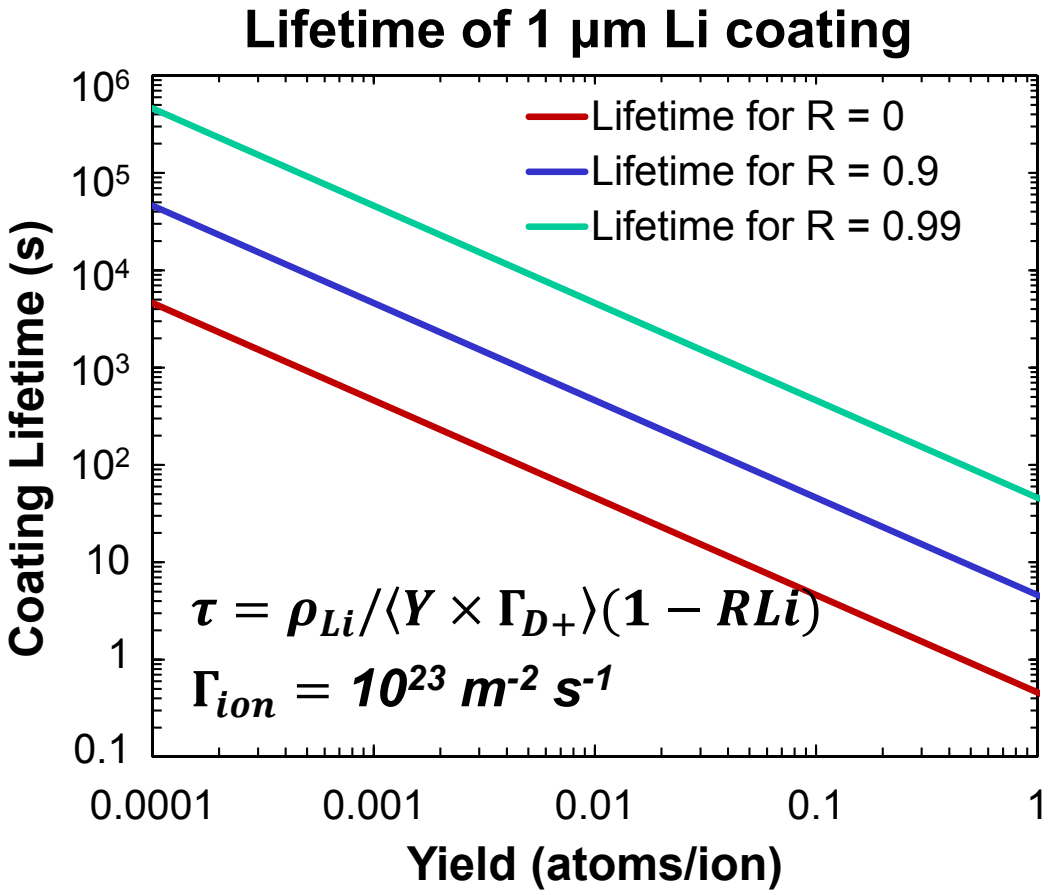


Motivation: Determining Li coating lifetimes is crucial for NSTX-U plasma performance

- NSTX-U candidate PFCs are Li/B-coated graphite, TZM
- Li lifetime τ determined by:
  - Areal density ρ_{Li}
  - Yield $Y_{Li} = \Gamma_{Li,out} / \Gamma_{D+,in}$
  - Ion flux Γ_{D+}
  - Re-deposition fraction R_{Li}
- Investigate Y_{Li} and R_{Li} in NSTX-U divertor regime:
  - $T_{surf} > 500$ °C
  - $E_{D+} < 50$ eV
  - $n_e > 10^{19}$ m^{-3}
- Will focus primarily on Y_{Li}



Empirical estimation of Li loss mechanisms during plasma exposure

- Sputtering: $Y_{sputt} = Y_{coll} + Y_{thermal}$
  - Collisional sputtering (TRIM)[1]
  - Thermal sputtering[2]:

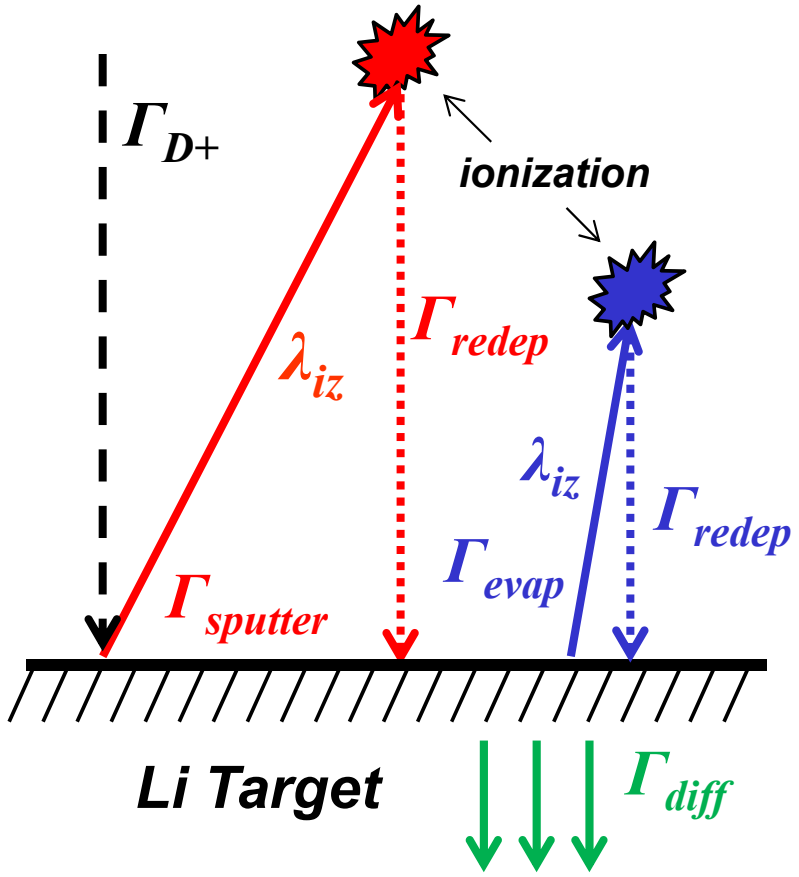
$$Y_{thermal} = \frac{A}{\sqrt{T_{Li} + B}} \exp\left(-\frac{U_{Li}}{k(T_{Li} + B)}\right)$$

- Evaporation (Langmuir law)

$$Y_{evap} = \frac{1}{\Gamma_{D+}} \frac{p_{Li}}{\sqrt{2\pi m_{Li} k T_{Li}}}$$

- 1-D diffusion into graphite[3]:

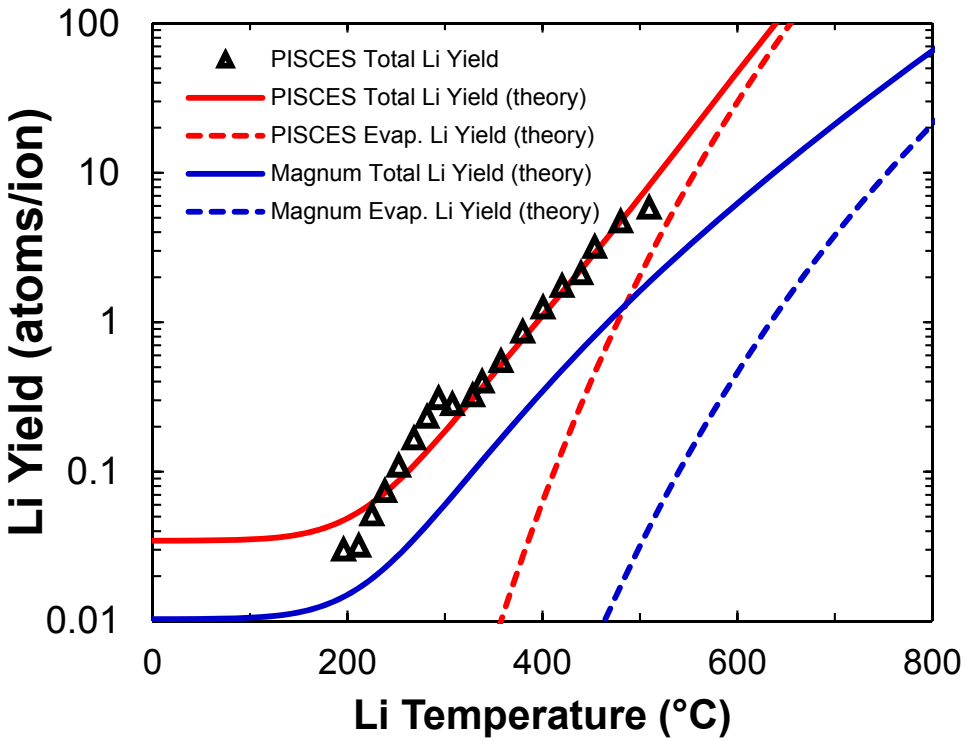
$$D_{\perp}\left(\frac{cm^2}{s}\right) = 4.5 \times 10^{-6} \exp\left(\frac{-0.26\ \mathrm{eV}}{\mathrm{kT_{Li}}}\right)$$



[1] J. Laszlo and W. Eckstein, JNM 184 (1991) 22-29.
[2] J.P. Allain et al., Phys Rev B 76 (2007)
[3] N. Itou et al., JNM (2001) 281-285.

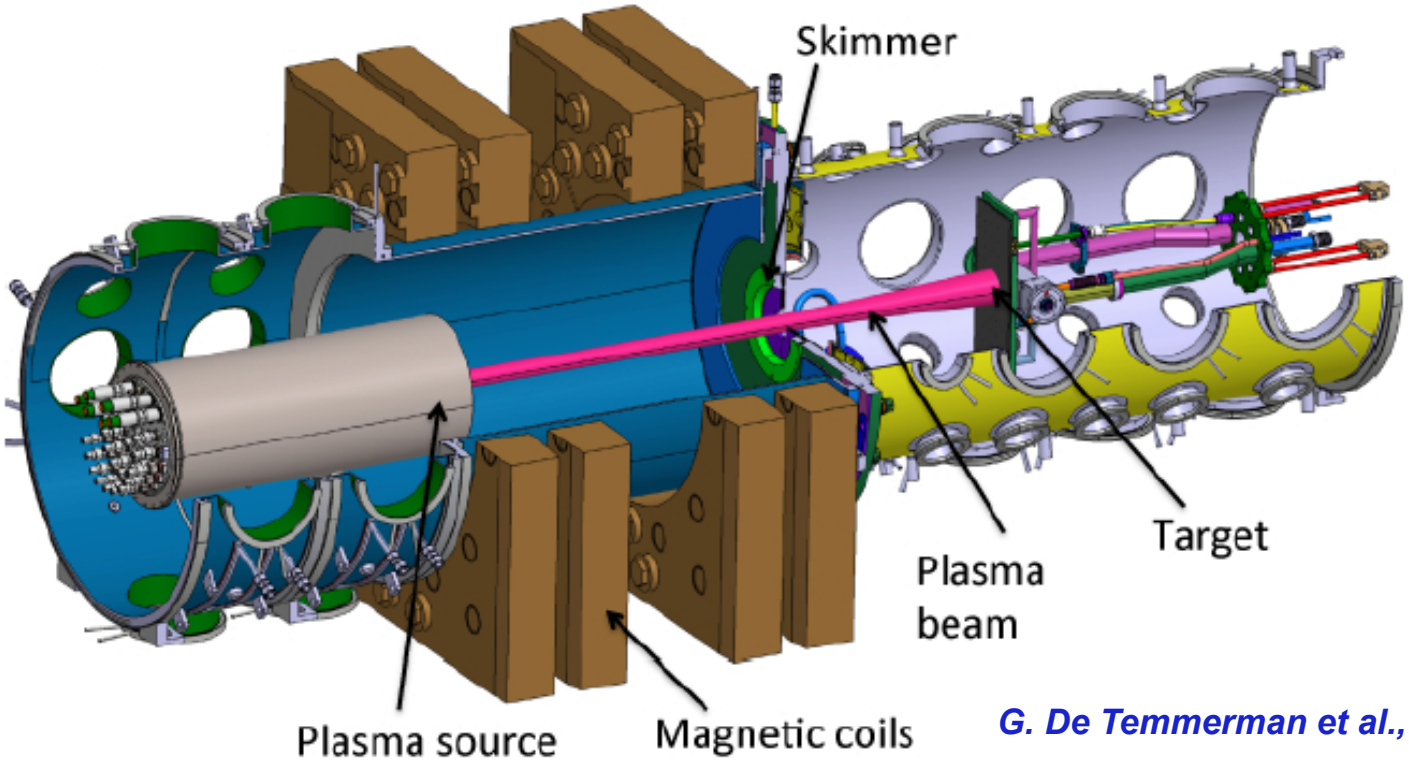
Empirical estimation of temperature-dependent Li yield for high-Z substrates ($D_\perp$=0)

- Use PISCES data[4] with ***A*** and ***B*** as fit parameters
  - E_{D+} = 50 eV
  - $\Gamma_{D+} \sim 10^{21}$ m^{-2} s^{-1}
- Extrapolate to Magnum-PSI/NSTX-U
  - E_{D+} = 20 eV
  - $\Gamma_{D+} \sim 5*10^{23}$ m^{-2} s^{-1}
- Evaporation will not dominate below 800 °C in Magnum-PSI or NSTX-U



[4]R.P. Doerner et al., JNM 290-293 (2001) 166-172

Magnum-PSI linear plasma device ideal for testing model

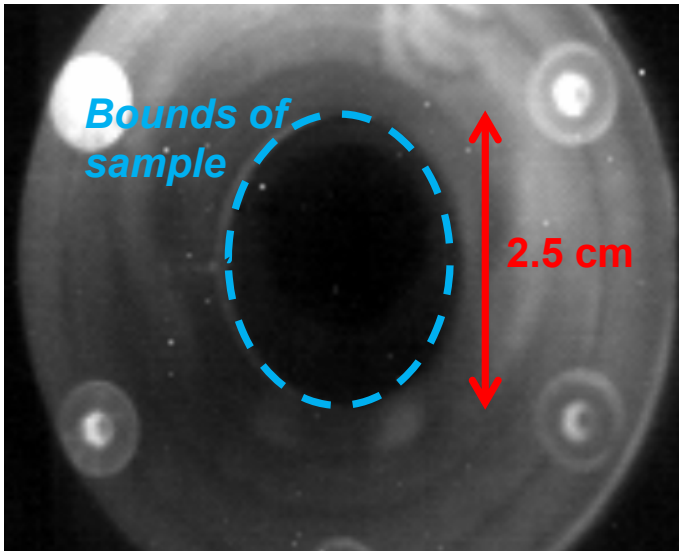


G. De Temmerman et al., FED 2013

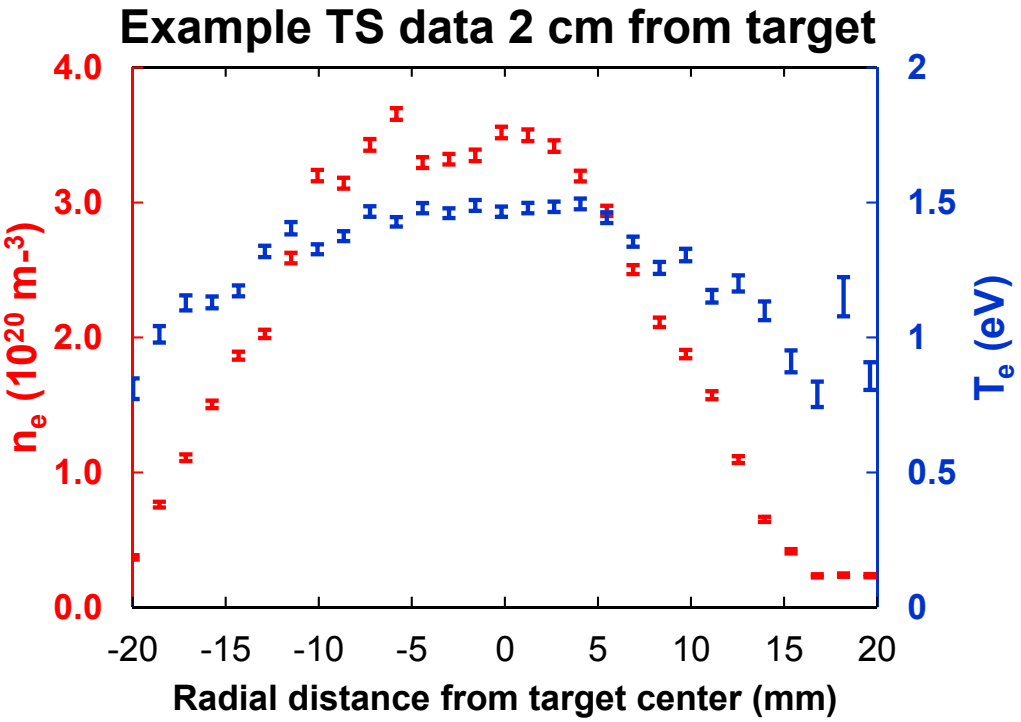
- $\Gamma_{D+} \lesssim 10^{24}$ m^{-2}s^{-1}, $T_e \lesssim 3$ eV, $n_e \lesssim 8*10^{20}$ m^{-3}
- 7 s pulses, B = 0.25 T at target
- Normal incidence: no magnetic pre-sheath
- Evaporative Li coatings applied in-vacuum

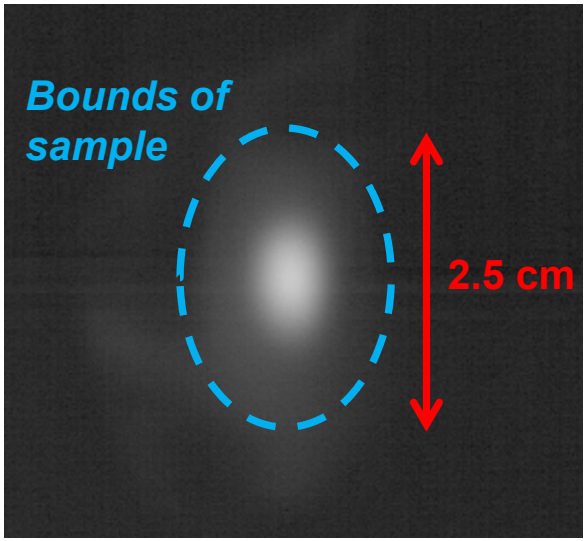
Diagnostic suite provides detailed measurements of plasma and surface

- **$n_e(r,z)$, $T_e(r,z)$:** Thomson scattering
- **$n_{Li}(r)$:** derived from camera w/ Li-I filter
- **$T_{surf}(r)$:** IR camera
  - calibrated against spectrally-resolved pyrometer



IR image of sample





Example Fast Camera Image Li-I emission

Inferring Li yields from Li-I emission measurements

- Solve Li^0 continuity equation with boundary condition:

$$\frac{\partial n_{\mathrm{Li}}}{dt} + \nabla \cdot (n_{\mathrm{Li}} v_{\mathrm{Li}}) = -n_{\mathrm{Li}} n_e S_{Li}$$

v_{Li} = 5200 m/s (1 eV)

S_{Li}: Ionization rate coefficient (ADAS)

$$n_{Li} v_{Li}\Big|_{z=0} = Y_{Li} \times \Gamma_{D+}$$

- Solve for $n_{Li}(r, z, Y_{Li})$
- Model for Li-I photons / m^2 s:

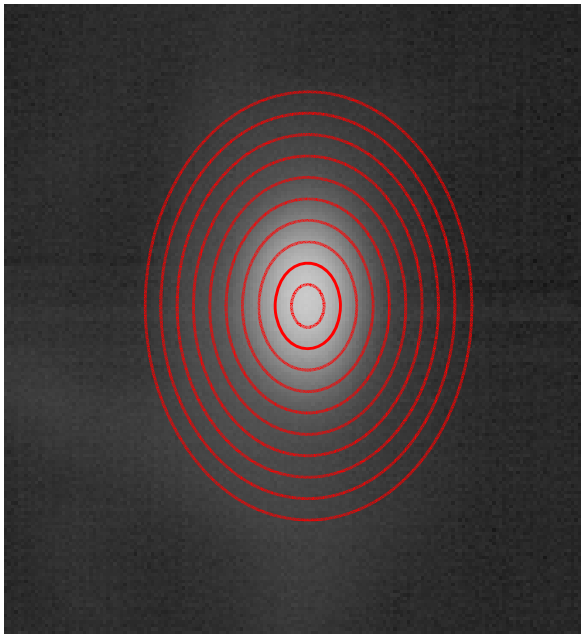
$$I_{Li,model} = \int_0^{z_0} n_{Li} n_e P_{Li} \, dz$$

P_{Li}: Photon emissivity coefficient (ADAS)

- Axially averaged measurement:

$$I_{Li,meas} = T \frac{\Omega_{pixel}}{4\pi} \left(\frac{photons}{s} \right)_{meas}$$

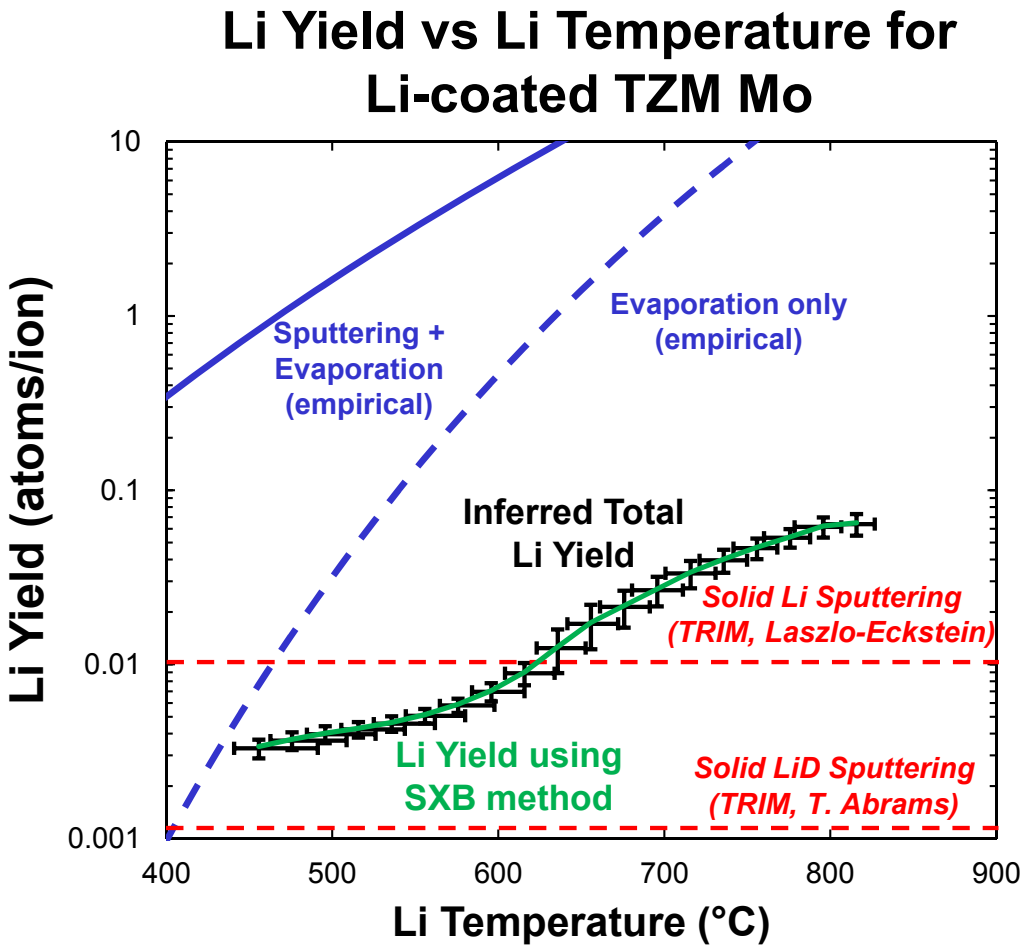
- Set $I_{Li,model} = I_{Li,meas} \rightarrow$ **infer** Y_{Li}



Axially average Li-I emission

Inferred Li yields in Magnum-PSI are much lower than predictions from empirical formula

- Suggests possible Li + (D/Mo) interactions that suppress erosion
- Uncertainty in T_{Li}:
  - IR meas. spread
  - Possible temp. dependence of Li emissivity[5]
- Uncertainty in Y_{Li}:
  - Phantom meas. spread
  - Thompson n_e/T_e error bar



For $n_e = 10^{21}$ m^{-3}, Te = 0.5 eV:

$$\left\langle \frac{Y_{Li,PEC}}{Y_{Li,SXB}} \right\rangle \approx 1.8$$

[5] *T.J. Tanaka et al., APEX Meeting, April 24-25, 2001*

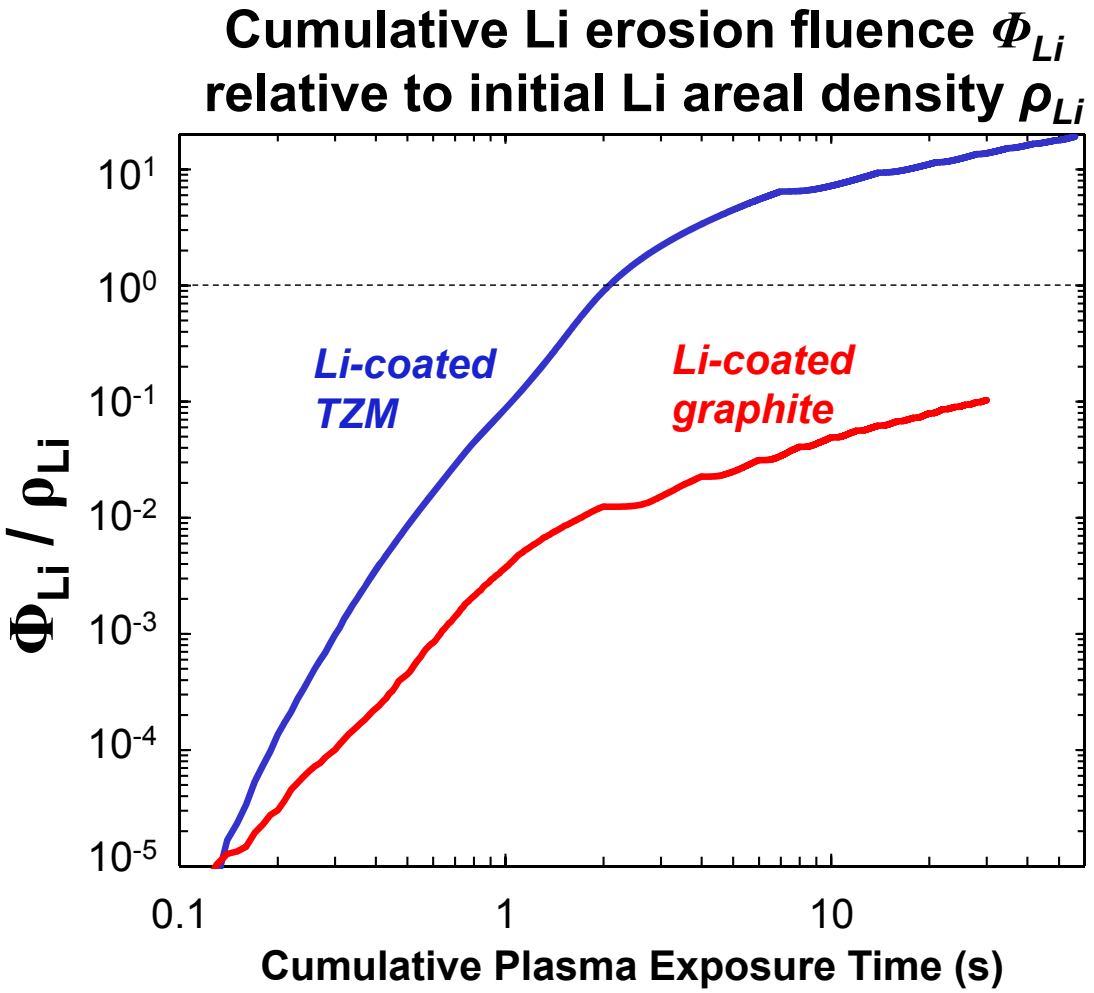
Li-coated graphite shows evidence of Li depletion before entire coating erodes into plasma

- Only 10% of Li on graphite erodes into plasma

$$\Phi_{Li}(t) = \int_0^t Y_{Li}(t')\Gamma_{D+}(t')\, dt'$$

- Suggests fast diffusion of Li into graphite occurred

- No Li on graphite surface post-mortem:



Discussion

- Observed Y_{Li} on TZM Mo << extrapolations from existing data
  - Suggests possible suppression of Li erosion via Li + D/Mo bonding
- Fast decrease in Li yield on Li-coated graphite possible indicator of Li diffusion into the bulk
  - Li coating persists longer on TZM Mo ($D_{\perp} = 0$, $R_{Li} > 0.95$)
  - Suggests Li on TZM will last significantly longer than Li on graphite in the NSTX-U divertor
- Future work
  - Post-mortem sample analysis to obtain re-deposition profiles
  - Investigate effects of Coulomb collisions & E fields[6]
  - Boron coatings
  - Oblique magnetic incidence

[6] *G.A. van Swaaij et al., "Erosion/redeposition modeling in an ITER divertor-like high-density, low-temperature plasma beam", in press*

Thank you!

- For more details:
  - Talk from PMIF-PFC 2013 Meeting (available online)
  - Upcoming Fus. Eng. Des. Paper

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