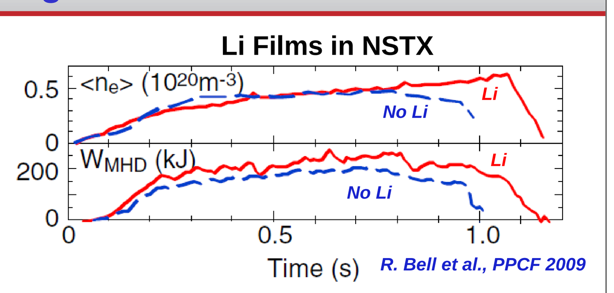
Suppressed gross erosion of high-temperature lithium films under high-flux deuterium bombardment

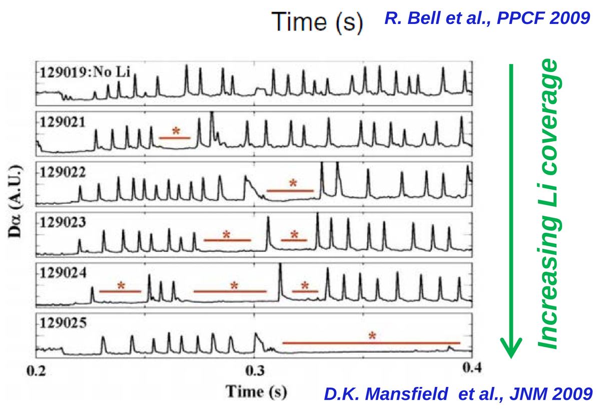
T. Abrams, M. A. Jaworski, R. Kaita, J. H. Nichols, D. P. Stotler, G. De Temmerman, M. A. van den Berg, H. J. van der Meiden, and T. W. Morgan

NSTX-U | PPPL Princeton Plasma Physics Laboratory | U.S. Department of Energy, Office of Science

Lithium improves plasma performance and protects underlying substrates

- Improved performance:
  - Increased n_e, W_{MHD}
  - ELM reduction
- Li protects even fragile porous substrates from high heat fluxes[a,b]
- Liquid Li is an alternative to W for a DEMO PFC
  - Self-healing under α/n bombardment
  - Eroded material can be replenished by flow





[a]G. Mazzitelli et al., FED 2010
[b]T. Abrams et al., JNM 2013

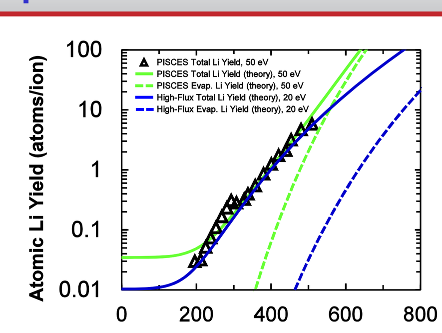
Recent results show that existing temperature limits for liquid Li may be pessimistic

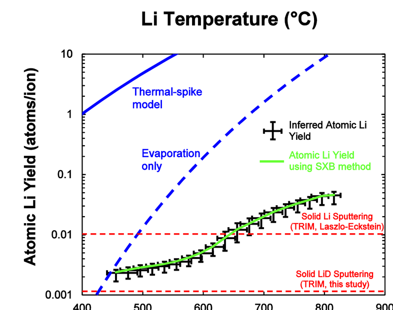
- Li erosion rate scales with temperature
  - Evaporation
  - Thermal sputtering
- Thermal-spike model of T-dependent Li sputtering[a]:

$$Y(T_{Li}) = \frac{A}{\sqrt{kT_{Li} + B}} \exp\left(\frac{-1.59 \text{ eV}}{\sqrt{kT_{Li} + B}}\right)$$

A,B: Fitting parameters
k: Boltzmann's constant

- But low-flux (10^{21} m^{-2} s^{-1}) data does not extrapolate to high fluxes (10^{24} m^{-2} s^{-1})





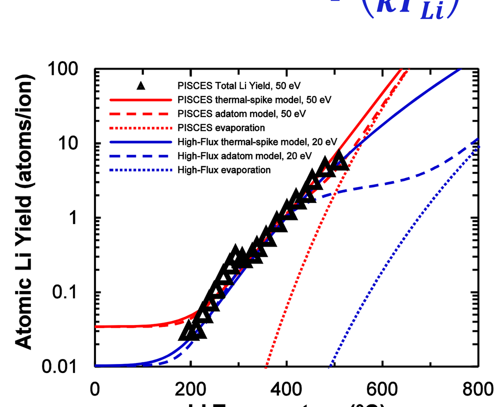
[a]J.P. Allain et al., Phys Rev B 2007
T. Abrams et al., FED 2014

Alternative model of thermally enhanced Li sputtering involves creation/evaporation of surface adatoms

- **Adatoms** are excited from their bound states, but not with sufficient energy to sputter[a]

$$Y(T_{Li}) = \frac{Y_{ad}}{1 + A\exp\left(\frac{E_{eff}}{kT_{Li}}\right)}$$

- Fitting parameters:
  - Y_{ad}: adatom yield
  - A, E_{eff}: constants associated with adatom creation/evaporation
- Predictions diverge from thermal spike model at D high fluxes & high Li temperatures

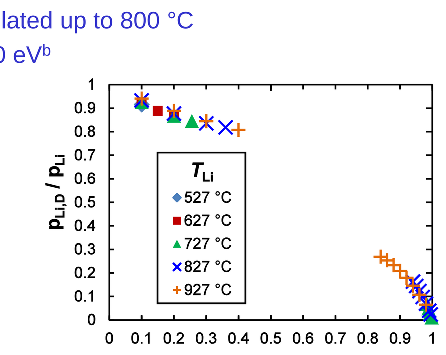


Li sputtering and evaporation are also reduced by mixed-material Li/D effects

- Previous work[a] found Y_{Li+D}/Y_L ~ 0.15-0.2 for 700 eV He→Li+D bombardment, attributed to preferential sputtering effects
- SRIM-TRIM calculations give Y_{Li+D}/Y_{Li} ~ 0.1 for 20 eV D →Li+D
- Caveats:
  - Room-temp BCA calculations are being extrapolated up to 800 °C
  - The assumptions in BCA break down below ~30 eV[b]
- Li vapor pressure above Li/LiD mixtures is reduced relative to pure Li

$$\Gamma_{evap}(T_{Li}) = \frac{p_{Li,D}}{\sqrt{2\pi m_{Li} k T_{Li}}}$$

Γ_{evap}: Evaporative Li flux
p_{Li}: Li vapor pressure
m_{Li}: Li mass (6.941 amu)



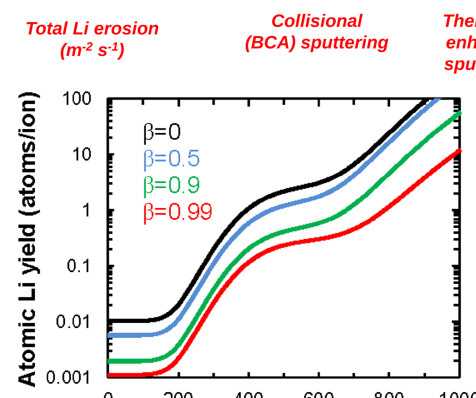
[a]J.P. Allain et al., PRB 2007
[b]W. Eckstein et al., 1995

Corrected Li erosion model is a function of Li temperature and D concentration in the Li

- Assume sputter yield reduced by ratio β of D/Li atoms on surface

$$\Gamma_{Li}(T_{Li}, \beta, \Gamma_{D+}) = \Gamma_{D+}[Y_{coll} + Y_{thermal}(T_{Li})](1 - 0.9\beta) + \frac{p(T_{Li}, \beta)}{\sqrt{2\pi m_{Li} k_B T_{Li}}}$$

Total Li erosion (m^{-2} s^{-1}) | Collisional (BCA) sputtering | Thermally-enhanced sputtering | Mixed-material reduction factor | Li evaporation

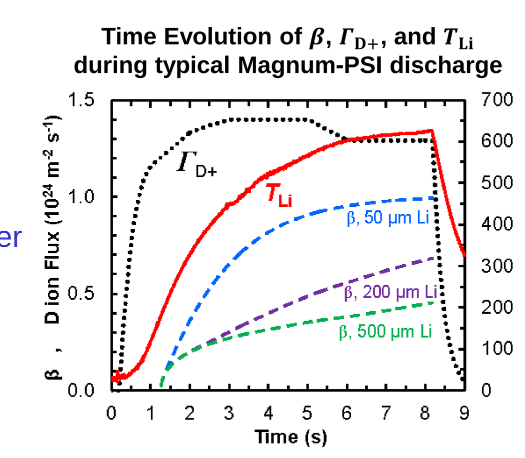


- Yield "plateaus" between 400-600 °C before increasing again due to evaporation

[a]J.P. Allain et al., PRB 2007
[b]W. Eckstein et al., 1995

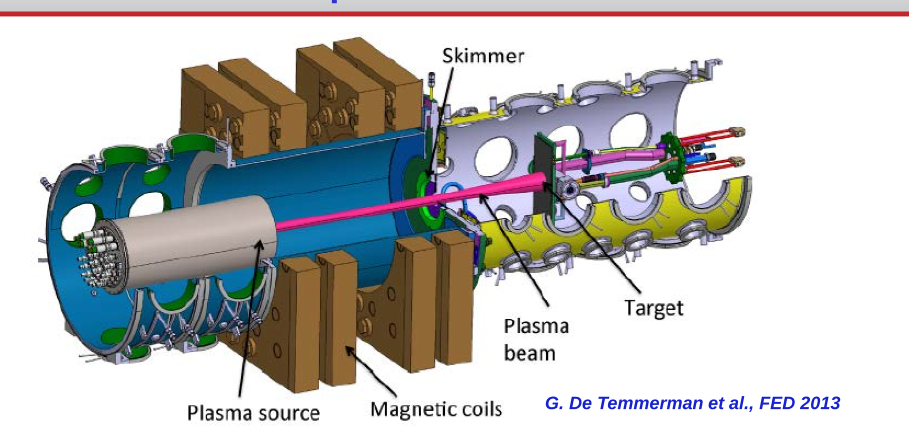
Mixed-material Li erosion model can be tested by varying 1) ion species 2) total D fluence

1. Measure Li erosion rate during Ne plasma bombardment
   - Ne is not retained in or chemically reactive with Li
   - Thus model predicts no reduction in erosion rate at high fluxes
2. Measure Li erosion rate as β changes dynamically
   - $\beta(t)$ can be predicted using 1-D diffusion model for D in Li[a]
   - Requires thick (≥ 50 µm) Li layer so that β grows slow enough



[a]H. Moriyama et al., JNM 1992

Model tested and analyzed in Magnum-PSI linear plasma device

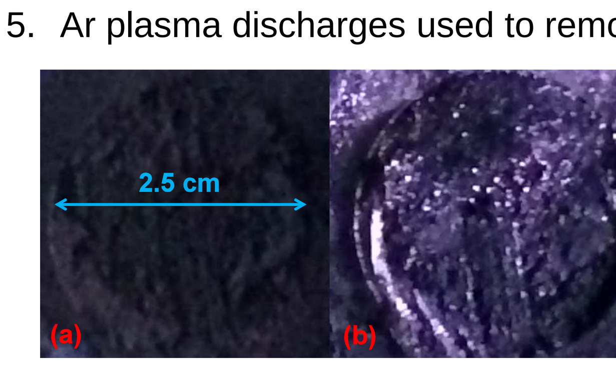


G. De Temmerman et al., FED 2013

- $\Gamma_{D+} \lesssim 2*10^{24}$ m^{-2}s^{-1}, $T_e \lesssim 3$ eV, $n_e \lesssim 8*10^{20}$ m^{-3}
- 5-10 s pulses, B = 0.25 T at target
- Normal incidence: no magnetic pre-sheath
- Thin evaporative Li coatings (≤ 1 µm) applied in-vacuum

New procedure developed for loading ≤ 500 µm thick Li targets in Magnum-PSI sample holder

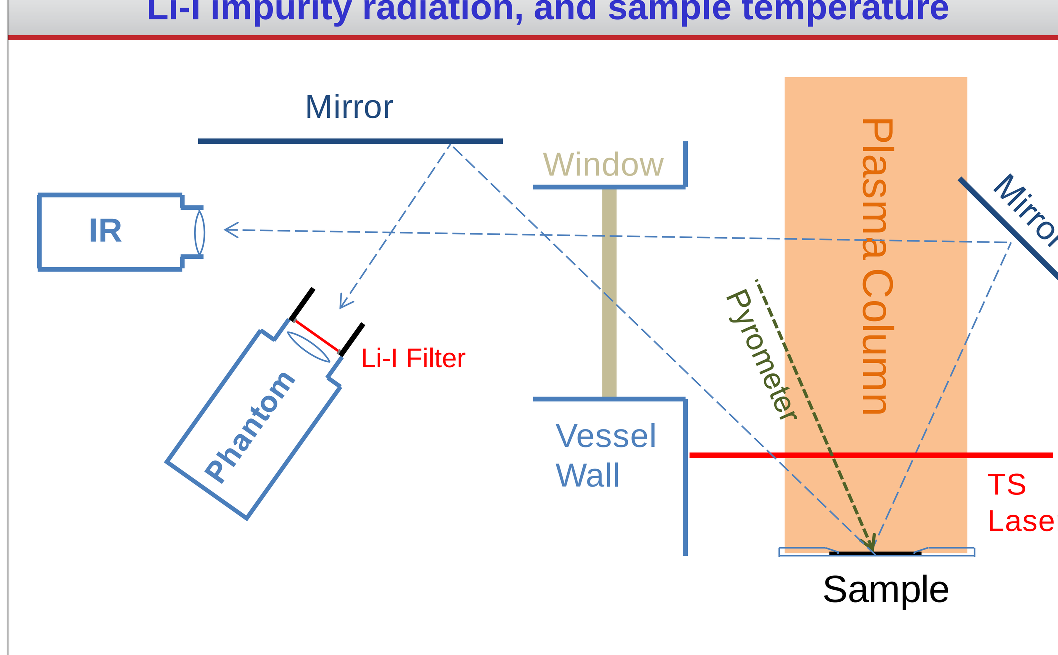
1. Li melted into sample wells inside Ar glove box
2. Sealed with SS shim stock covers & heat-seal mylar bags
3. SS cover remained on sample during mounting
4. Li exposed to atmosphere for 20-30 s between cover removal & vessel pumpdown
5. Ar plasma discharges used to remove oxide coating from Li



Ar plasma discharge cleaning.

Li surface transformed from dark to shiny.

Diagnostic suite provides measurements of plasma n_e/T_e, Li-I impurity radiation, and sample temperature



Inferring Li yields from Li-I emission measurements

- Solve Li[0] continuity equation with boundary condition:

$$\frac{\partial n_{Li}}{dt} + \nabla\cdot(n_{Li}v_{Li}) = -n_{Li}n_e S_{Li} \qquad n_{Li}v_{Li}\Big|_{z=0} = Y_{Li} \times \Gamma_{D+}$$

v_{Li} = 5200 m/s (1 eV); Ionization rate coefficient (ADAS)

- Solve for $n_{Li}(r, z, Y_{Li})$
- Model for Li-I photons / m² s:

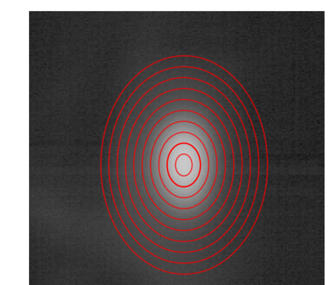
$$I_{Li,model} = \int_0^{z_0} n_{Li} n_e P_{Li} dz$$

Photon emissivity coefficient (ADAS)

- Axially averaged measurement:

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

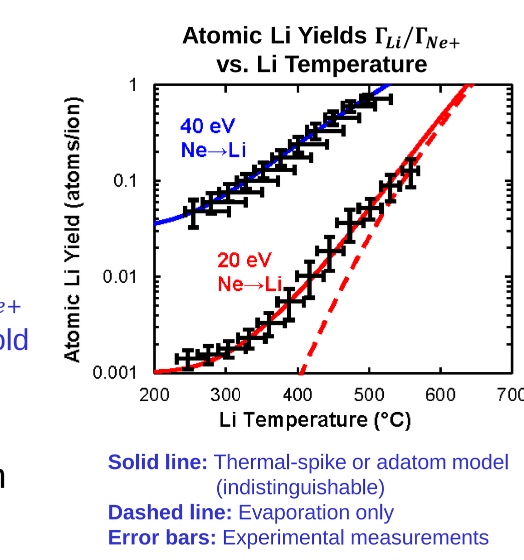
- Set $I_{Li,model} = I_{Li,meas}$ → **infer Y_{Li}**



Axially average Li-I emission

Li yields measured during Ne plasma bombardment at 20 eV and 40 eV ion energy

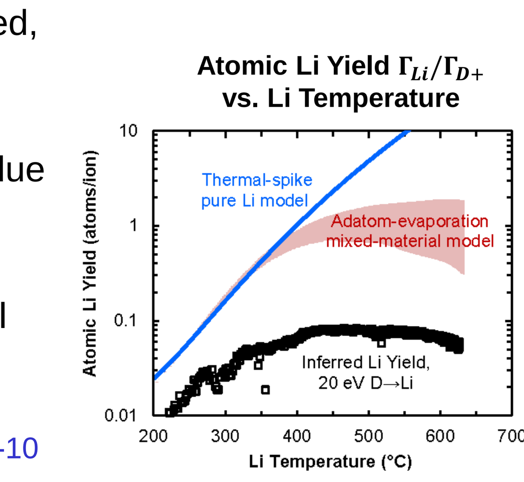
- Separate fitting parameters used for 20 & 40 eV cases
- 20 eV Ne→Li erosion much lower than 40 eV
  - Model predicts T-dependent sputtering is independent of E_{Ne+}
  - Suggests possible near-threshold effects
- 40 eV Ne →Li consistent with previous results for He →Li



Solid line: Thermal-spike or adatom model (indistinguishable)
Dashed line: Evaporation only
Error bars: Experimental measurements

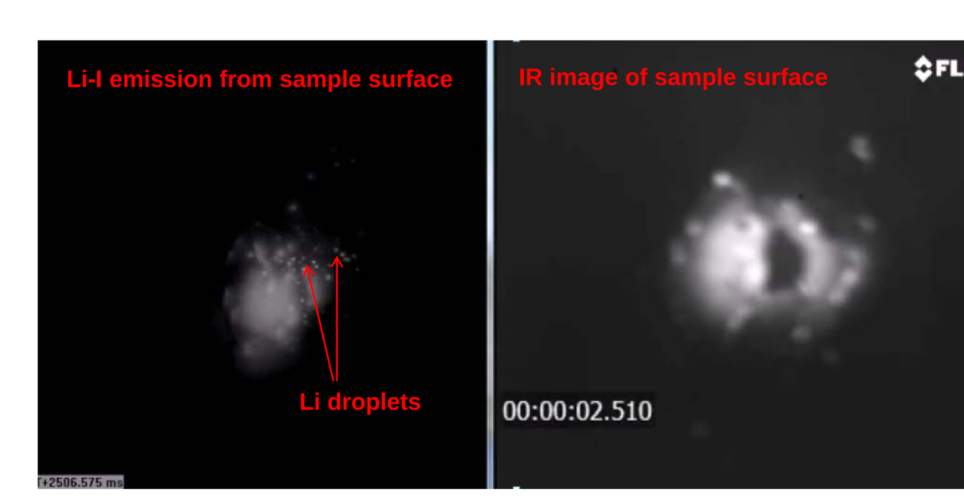
Li yields measured during D plasma bombardment compared to predictions of adatom mixed-material model

- Lots of Li melt motion observed, thus Li thickness is unknown
- Introduces error band on Y_{Li} due to unknown $\beta(t)$ (see slide 7)
- Adatom mixed-material model captures qualitative evolution of Li erosion rate
  - Absolute value off by factor of 5-10
  - Again suggests thermal sputtering is further reduced near energy threshold



Significant Li droplet ejection and melt motion observed during certain discharges

- Melt motion and droplet ejection observed (sometimes) during first 4-5 seconds of D plasma bombardment

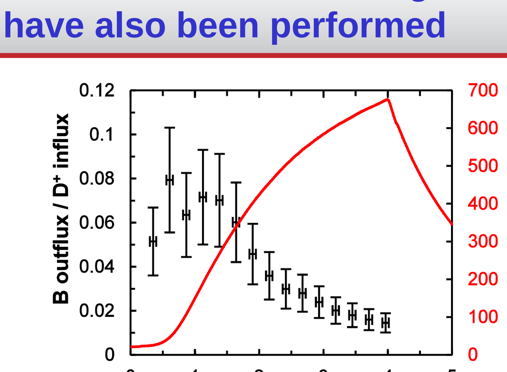


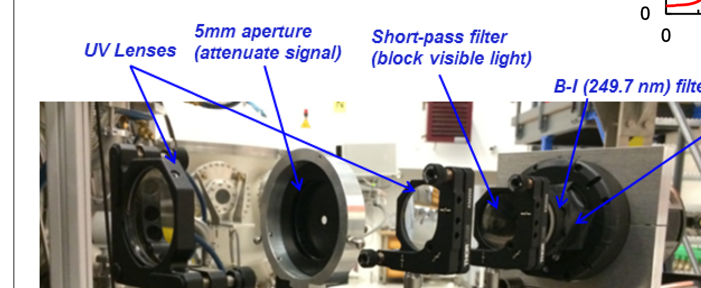
Conclusions

- Adatom-evaporation mixed-material model developed to predict temperature-dependent Li+D erosion rates
- Measured values of 40 eV Ne→Li erosion rates show consistency with results for 50 eV He→Li
- Model captures qualitative dependence of Li erosion yield for thick mixed-material Li/D layers
  - But absolute discrepancy of 5-10 between experiment & theory
  - Suggests thermal sputtering is reduced near E threshold
- **Temperature limits for Li-coated PFCs in a fusion reactor may be higher than previously envisioned**

Preliminary measurements of boron erosion under high-flux D plasma bombardment have also been performed

- 300 nm sputter-coated B layer on TZM Mo exposed to D plasma discharge
- Measure erosion via B-I emission (249.7 nm)





- $Y_B \gg$ previous measurement of 0.004[a] for 20 eV D→B
- Measured erosion rate implies depletion of boron layer after 1-2 s

[a]E. Hechtl et al., JNM 1992