NSTX-U

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Erosion and re-deposition of lithium coatings on TZM molybdenum and graphite during high-flux plasma bombardment

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and the NSTX-U Research Team

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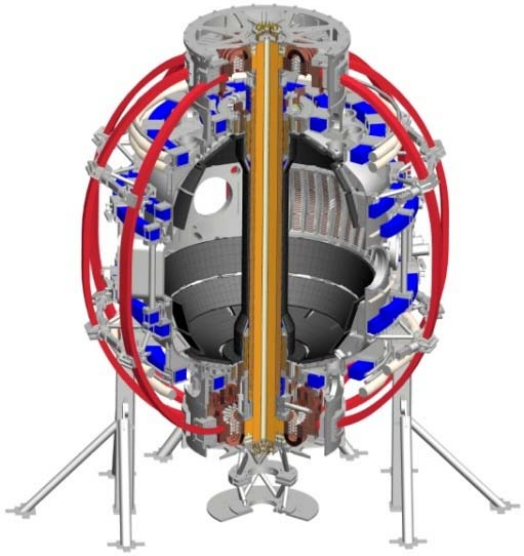
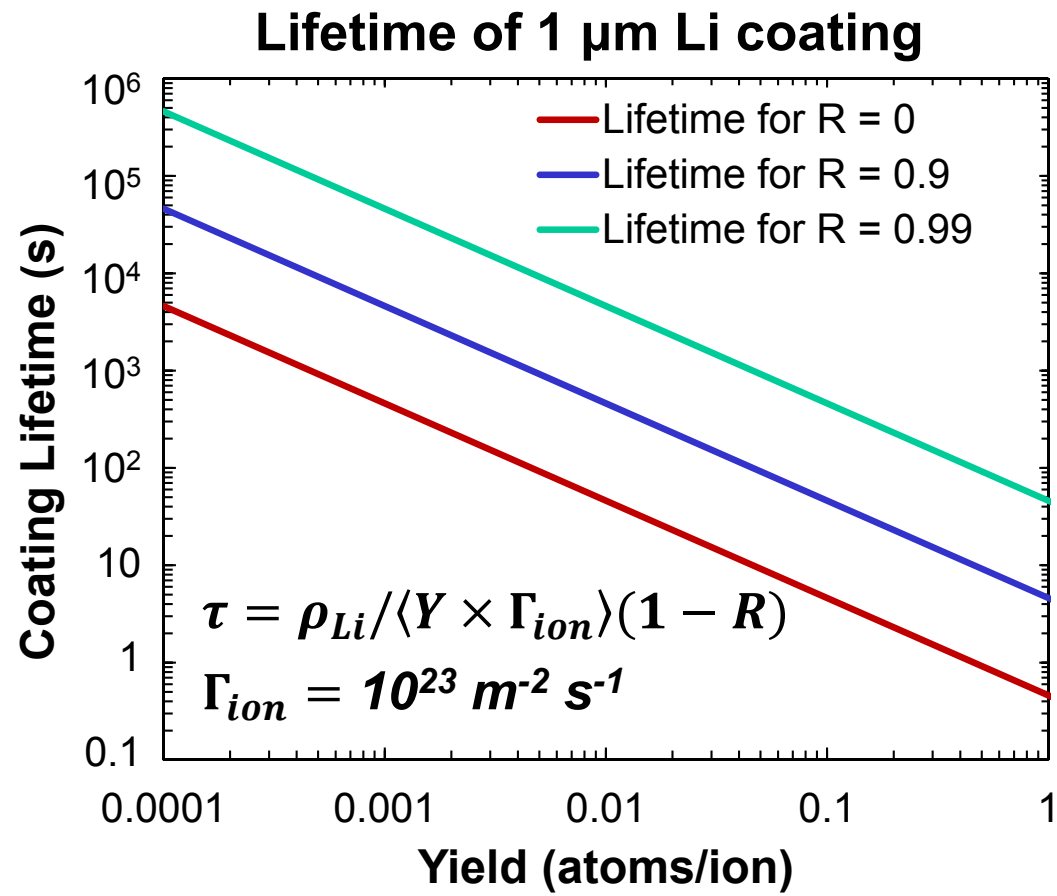


Motivation: Determining Li coating lifetimes is crucial for NSTX-U plasma performance

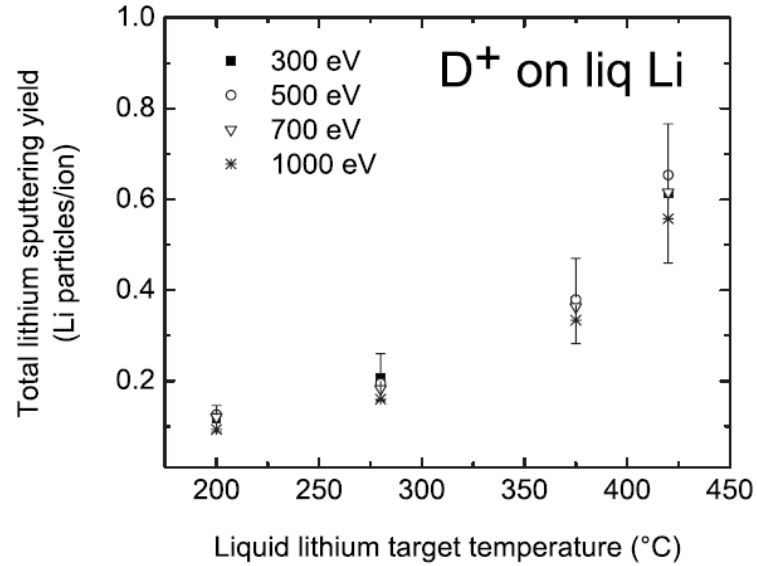
- NSTX-U candidate PFCs are B/Li-coated graphite and TZM
- Li lifetime τ determined by:
  - Coating areal density ρ_{Li}
  - Yield Y_{Li}
  - Ion flux Γ_{D+}
  - Re-deposition fraction R_{Li}
- Investigate Y_{Li} and R_{Li} in NSTX-U divertor regime:
  - $T_{surf} > 500$ °C
  - $E_{D+} < 50$ eV
  - $n_e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



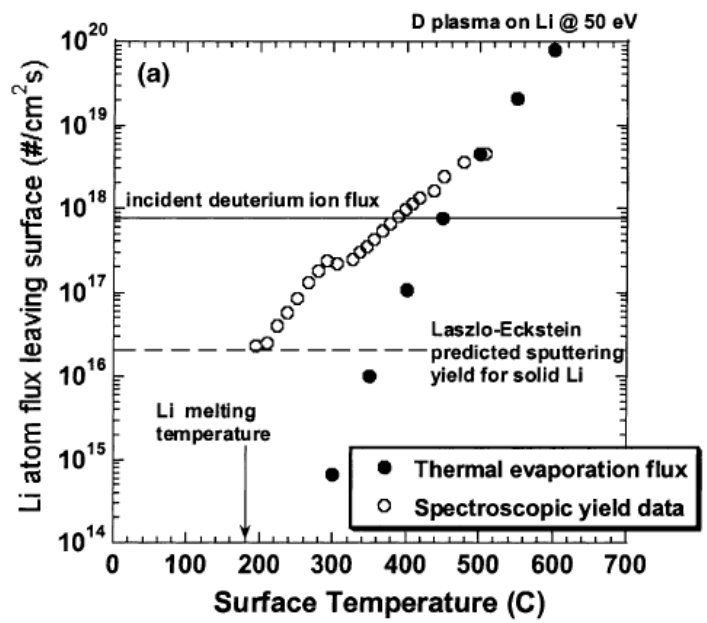
Previous Li yield measurements limited to < 500 ˚C and no re-deposition

- Allain et al. show modest increase in Y_{Li} for T < 450 ˚C for flux of ~10^{14} $m^{-2}s^{-1}$
- Doerner et al. also shows temperature dependence at ~10^{18} $m^{-2}s^{-1}$ (n_e ~ 10^{18} m^{-3})
- J.N. Brooks predicts* R ≳ 0.95 for a liquid Li divertor (200 eV, 10^{19} m^{-3}) and 1.0 for conventional divertor

J.N. Brooks et al., JNM 2001



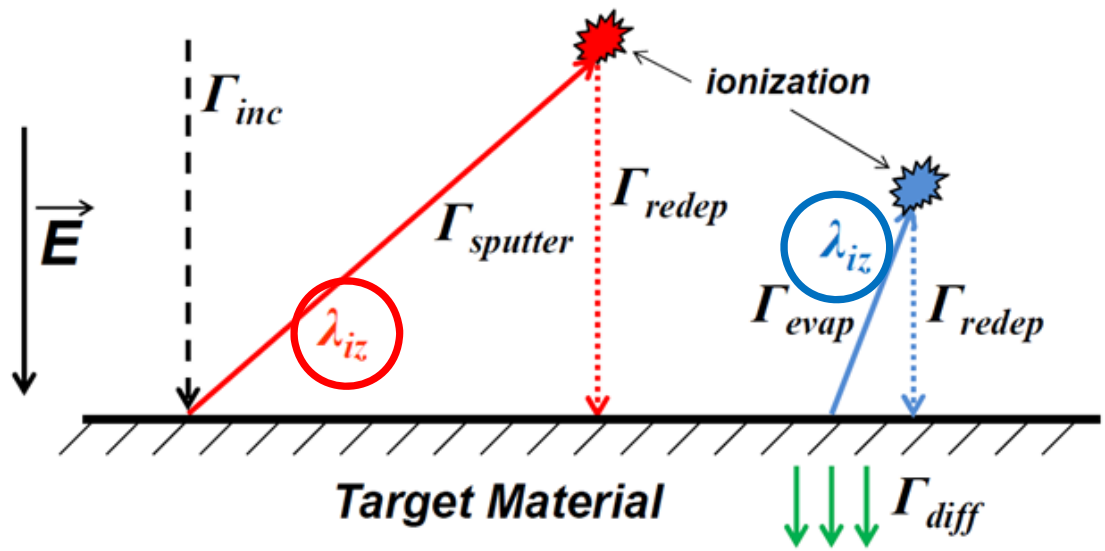
J.P. Allain et al., Phys Rev B 2007



R. Doerner et al., JNM 2001

Semi-analytic model under development for simulating dominant mechanisms of atom loss/gain in thin films

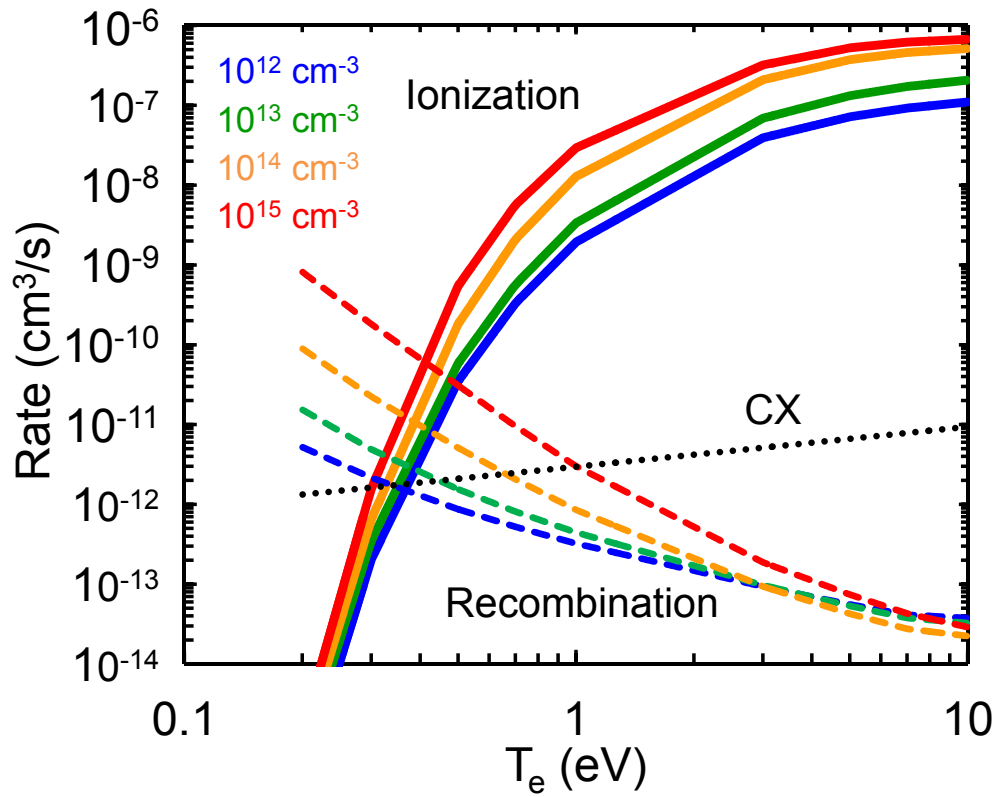
- Coating areal density ρ_z (atoms / m^{-2}) reduced by:
  - Sputtering (TRIM)
  - Evaporation (Langmuir law)
  - 1-D diffusion into the material (**graphite:** Itou JNM 2001)
- ρ_z can also increase due to ionization/re-deposition



$$\frac{d\rho_z}{dt} = \Gamma_{\text{net}} = \Gamma_{\text{redep}} - \overbrace{\left(\Gamma_{\text{sputt}} + \Gamma_{\text{evap}} + \Gamma_{\text{diff}}\right)}^{\Gamma_{\text{gross}}^{\text{loss}}} = (R-1)\Gamma_{\text{gross}}^{\text{loss}}$$

Li re-deposition fraction depends primarily on ionization rates obtained from ADAS collisional-radiative model

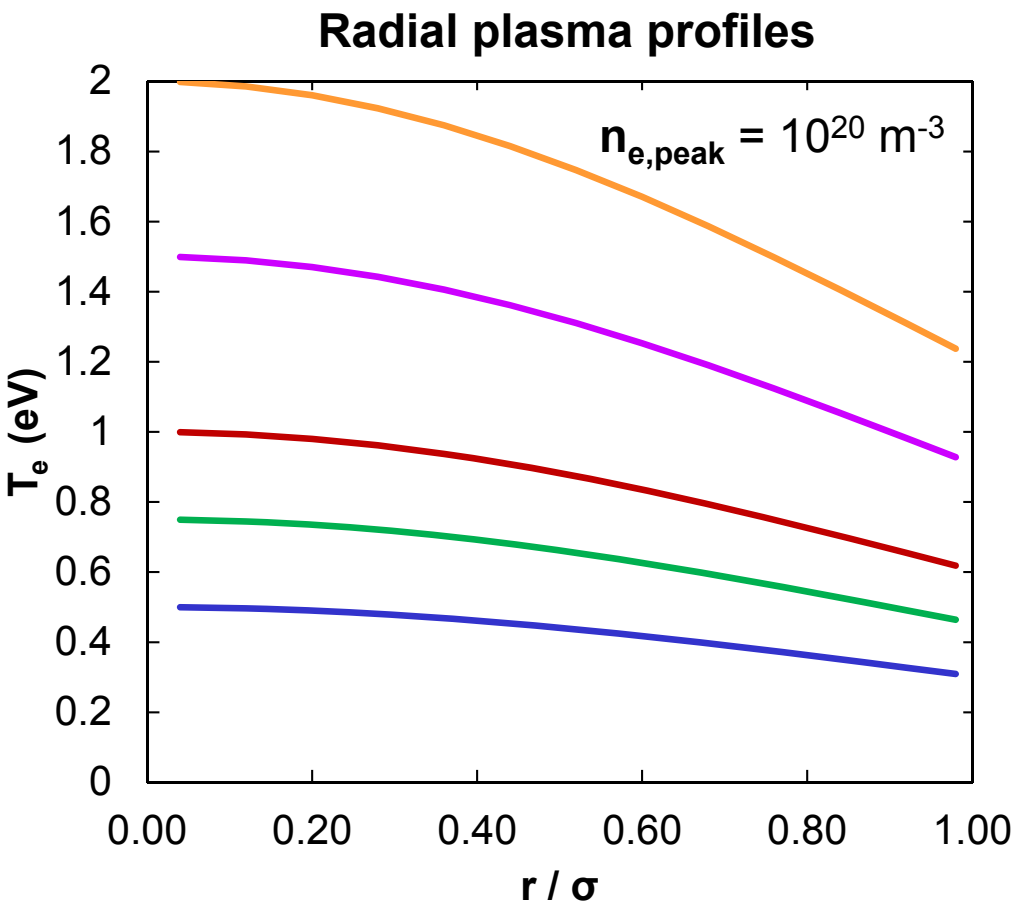
- Assumptions:
  - Steady state (t_{ionize} ~ 1 μs)
  - All sputtered ions promptly re-deposit on target
  - No recomb./CX
  - No ⊥ impurity transport
  - No secondary elect. emission
  - All Li^+ re-deposits on target due to biasing and plasma flow

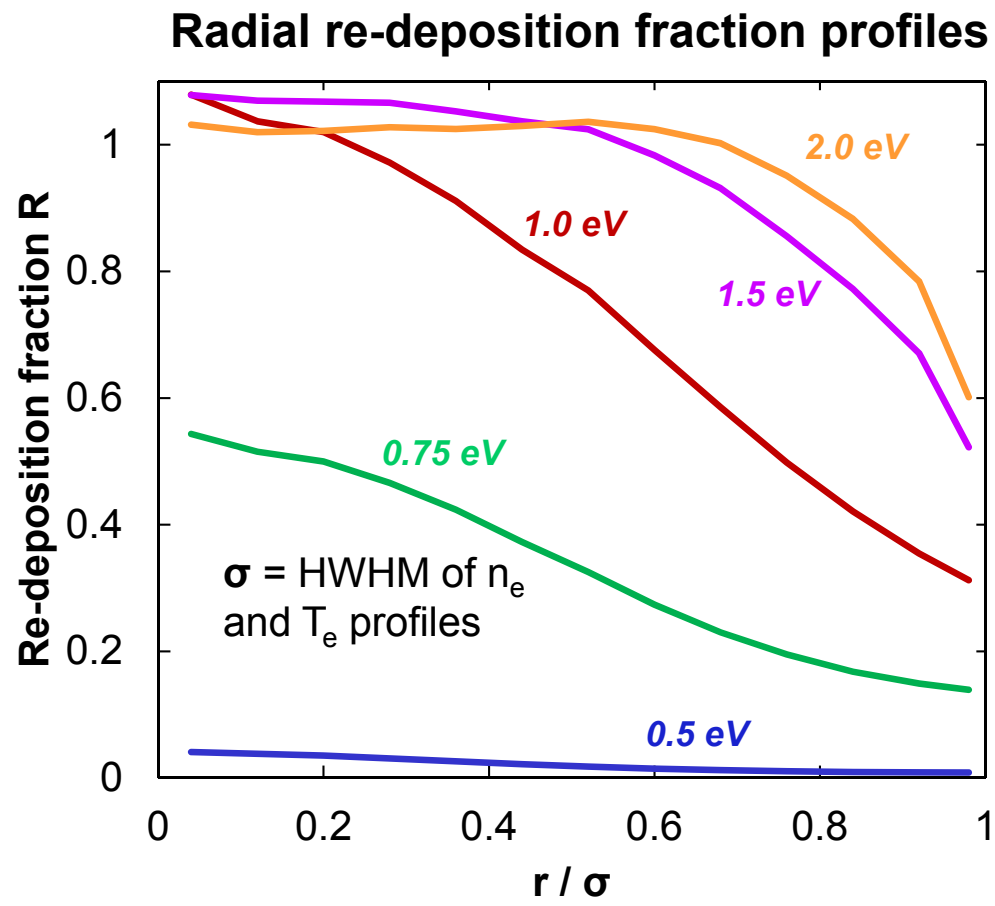


$$\frac{\partial n_{\mathrm{Li0}}}{dt} + \nabla \cdot (n_{\mathrm{Li0}} v_{\mathrm{Li0}}) = -n_{\mathrm{Li0}} n_e S + n_{Li+} n_e R + n_{Li+} n_D C$$

*H.P. Summers, "Atomic Data and Analysis Structure User Manual," 2004. (www.adas.ac.uk)

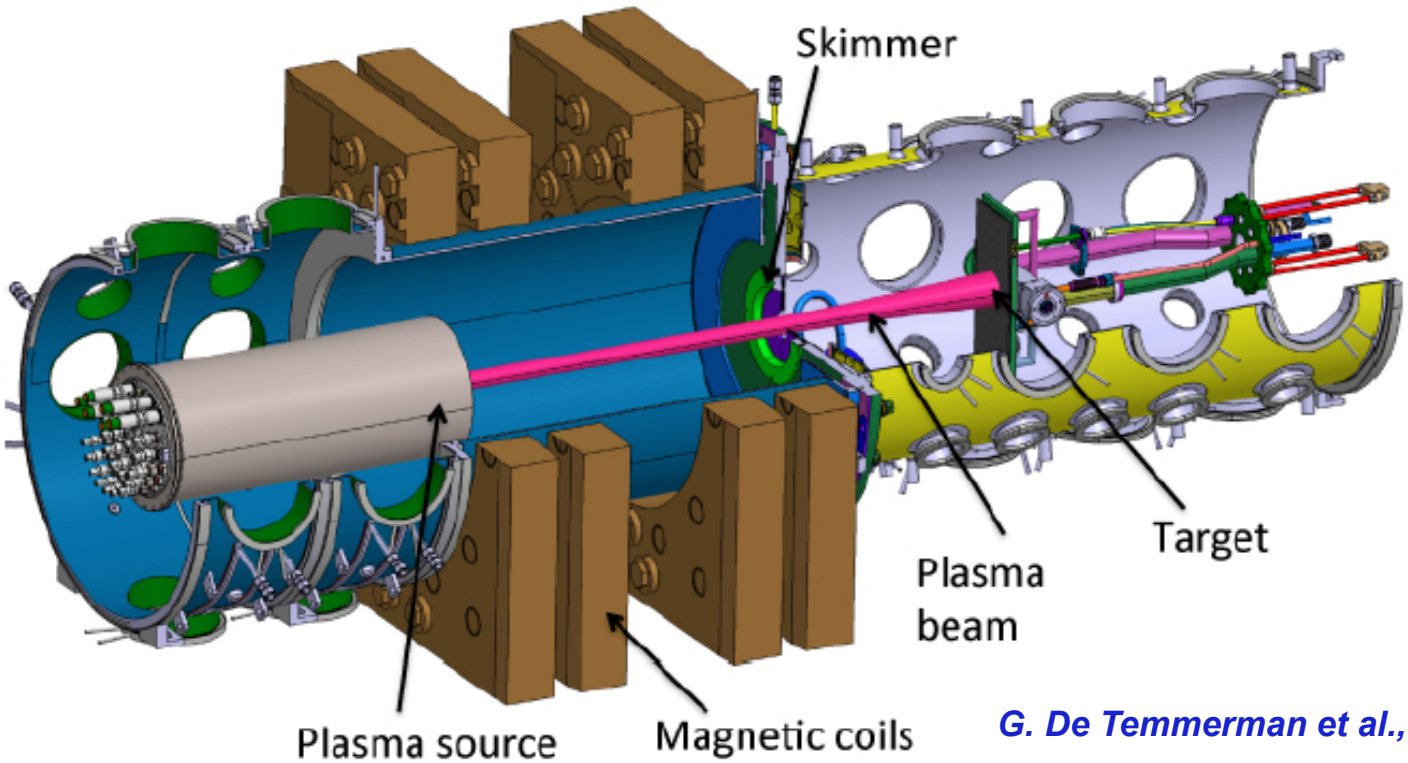
Predictions for re-deposition fraction of Li in a non-uniform plasma





- Plasma profile chosen to be 2D Gaussian with HWHM σ
- Circular Li target with boundary at r / σ = 1

Magnum-PSI linear plasma device ideal for testing model

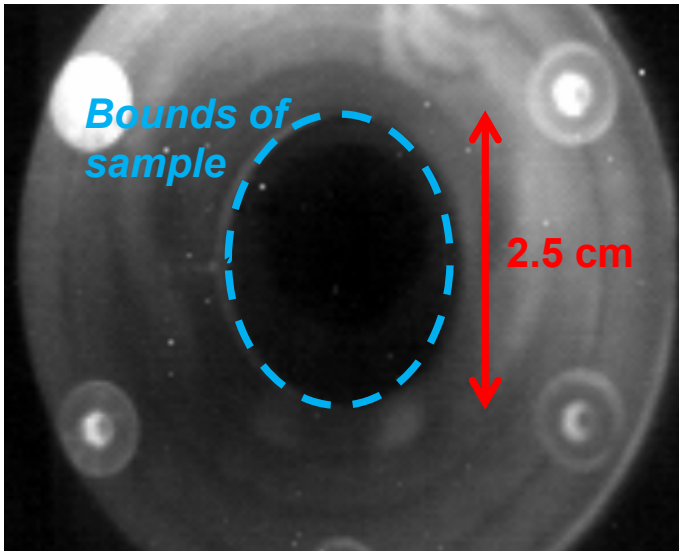


G. De Temmerman et al., FED 2013

- $\Gamma_{D+} \lesssim 10^{24}$ 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

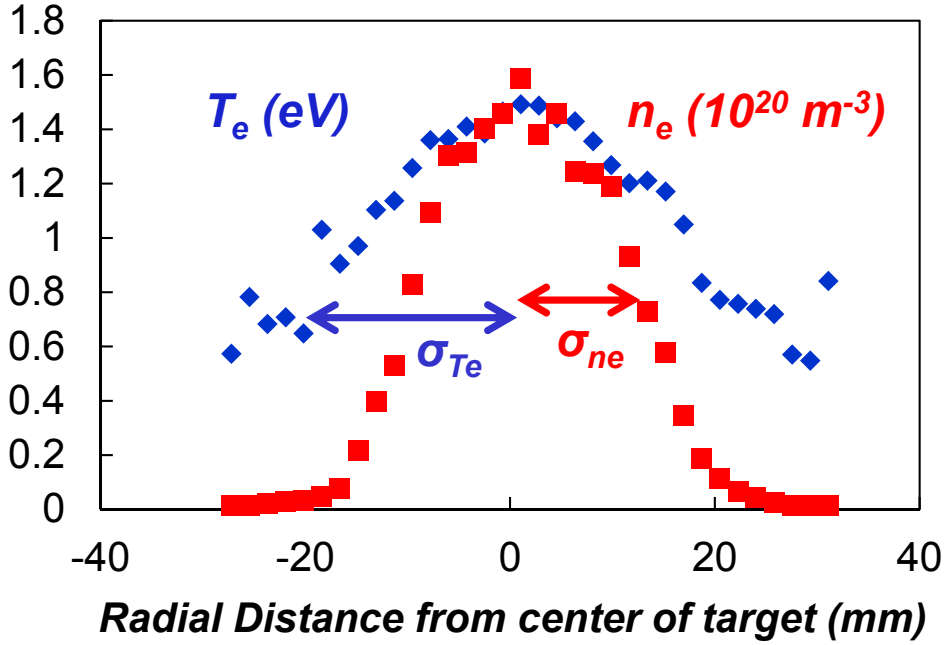
Diagnostic suite provides detailed measurements of plasma and surface

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

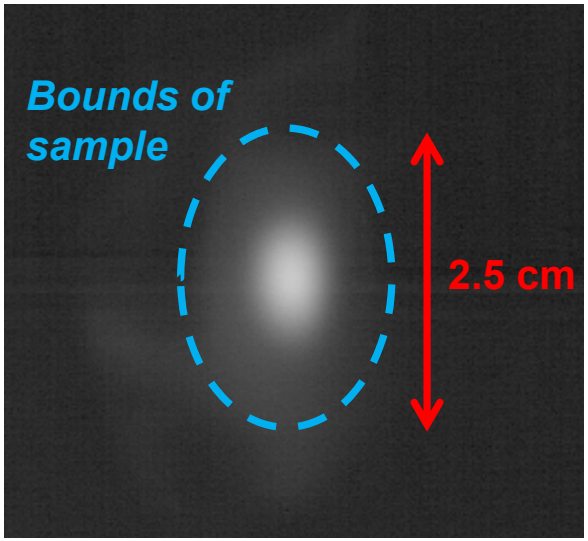


IR image of sample

Example Thomson Scattering Data



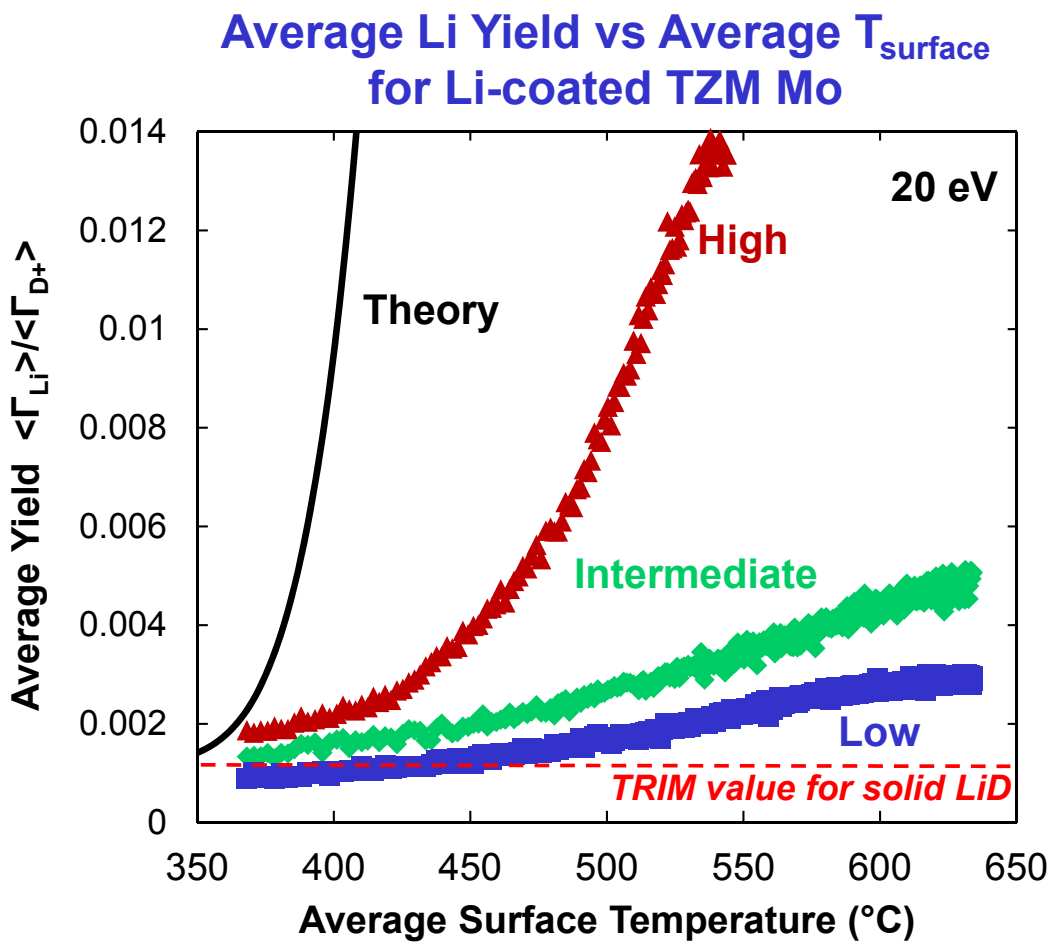
Example Fast Camera Image Li-I emission



Lithium yields inferred from measurements and modeling

- Three different erosion "regimes" observed for Li-coated TZM Mo
  - High-yield regime lasts 1-2 seconds ($\Phi_{D+}/\rho_{Li} \leq 250$)
  - Intermediate-yield regime lasts $\lesssim$ 30 s ($\Phi_{D+}/\rho_{Li} \leq 4300$)
  - Low-yield regime where Li has been depleted from center of sample

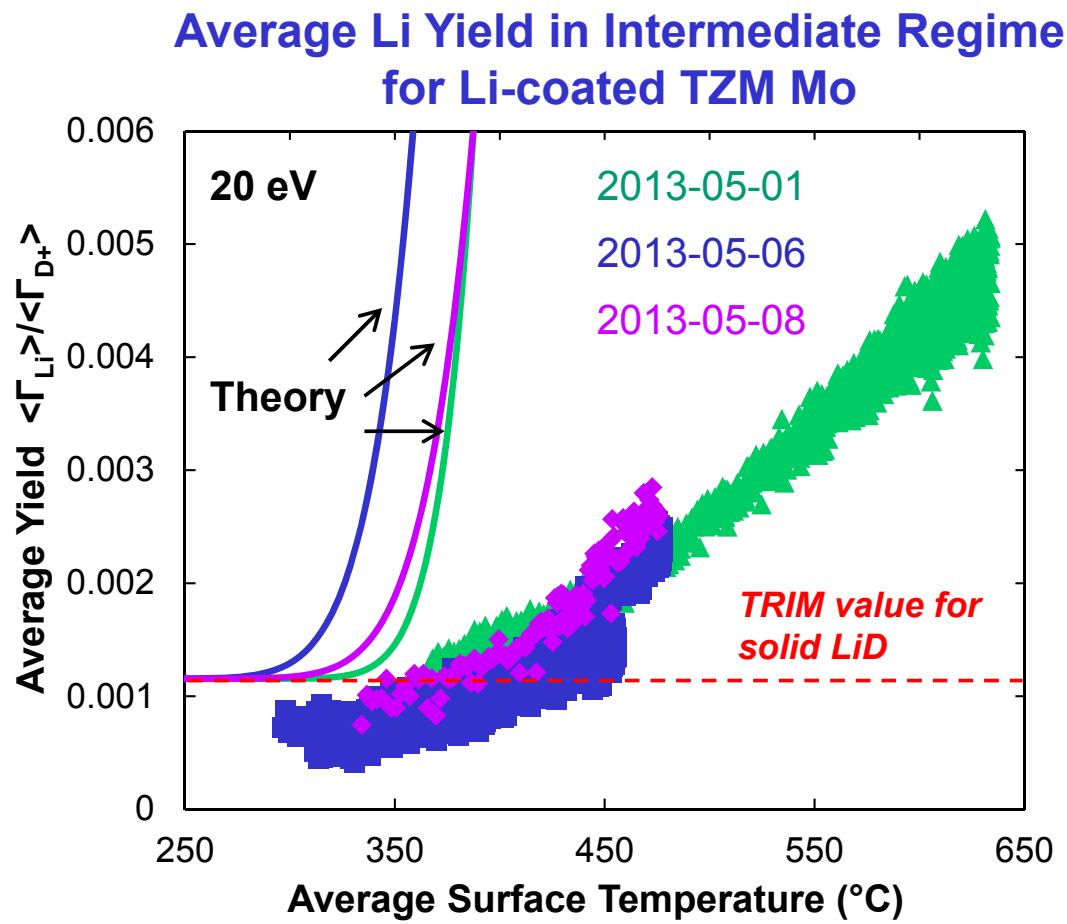
- Even high-yield regime shows significantly less erosion than Langmuir law evaporation + TRIM



$$Y_{theory} = Y_{TRIM} + \Gamma_{evap}/\Gamma_{D+}$$

Lithium yields in intermediate regime are not correlated with expected evaporation rates

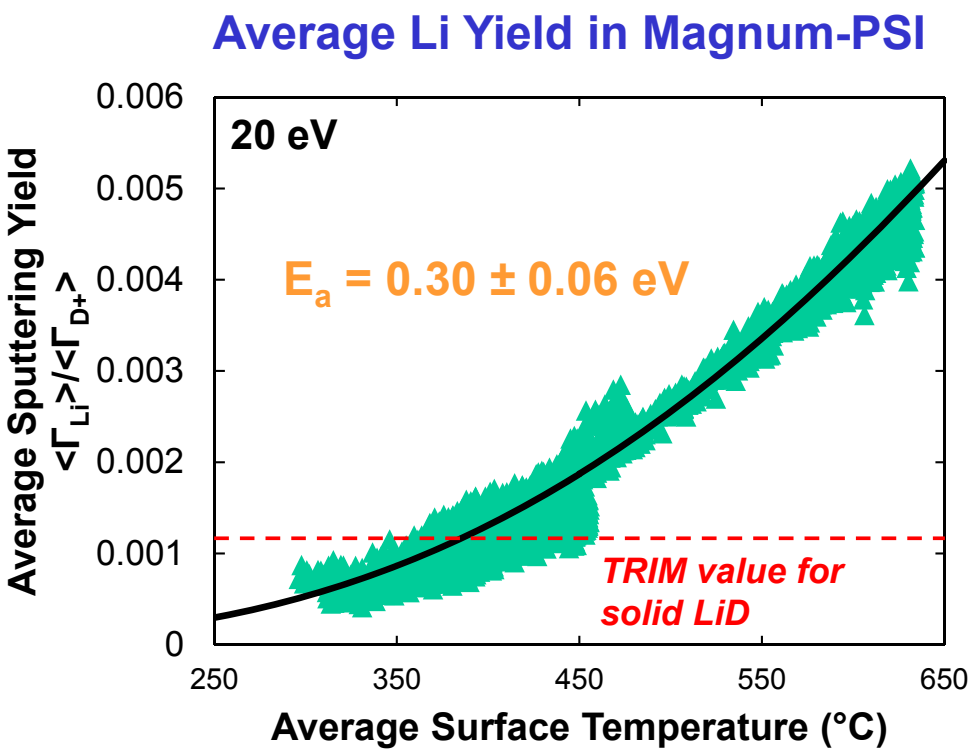
- Yields are consistent during different sets of exposures
- Not correlated with predictions from theory
- Suggests possible Li + (D/Mo) interactions that suppress erosion

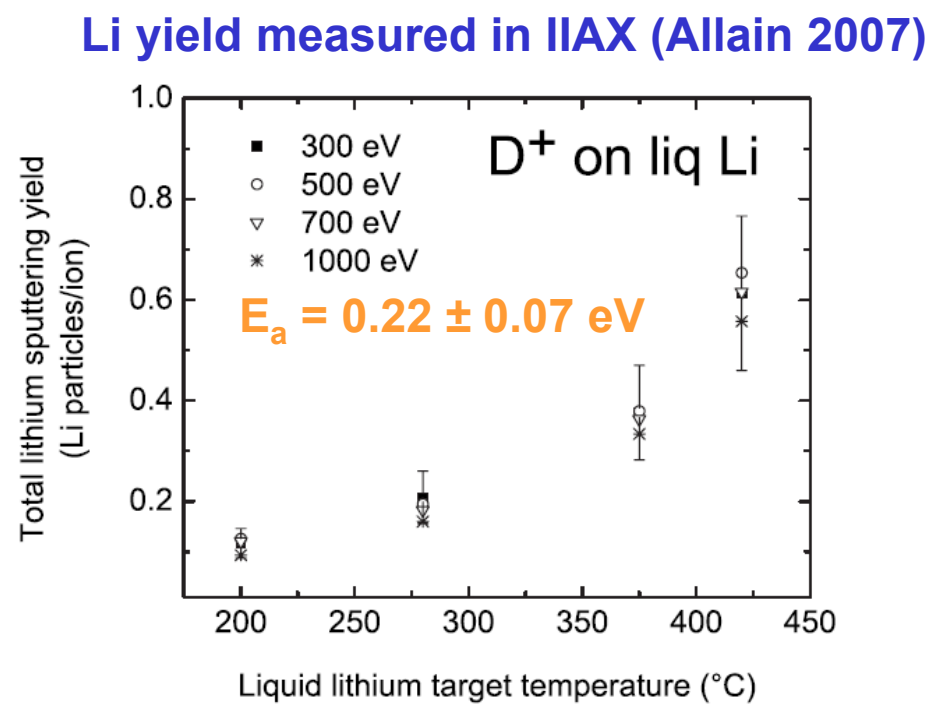


Date	$n_{e,peak}$	$T_{e,peak}$	σ_{ne}	σ_{Te}	σ_{Tsurf}
2013-05-01	$2.4*10^{20}$ m^{-3}	1.7 eV	9.5 mm	15.1 mm	13.1 mm
2013-05-06	$2.6*10^{20}$ m^{-3}	1.5 eV	10.0 mm	17.4 mm	9.8 mm
2013-05-08	$3.5*10^{20}$ m^{-3}	1.5 eV	10.4 mm	18.7 mm	10.8 mm

Preliminary analysis conducted to determine usefulness of Arrhenius rate description

- Assume Arrhenius rate: $Y_{Li} = A_0 \exp\left(-\frac{E_a}{k_B T}\right)$

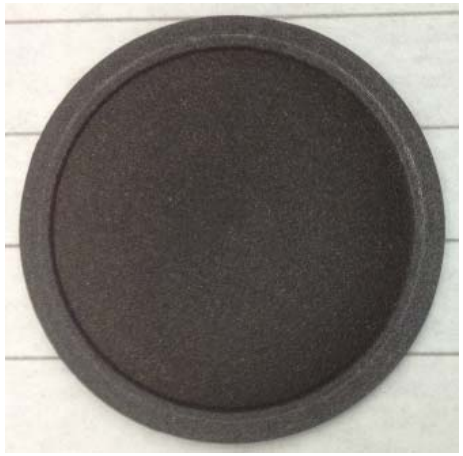


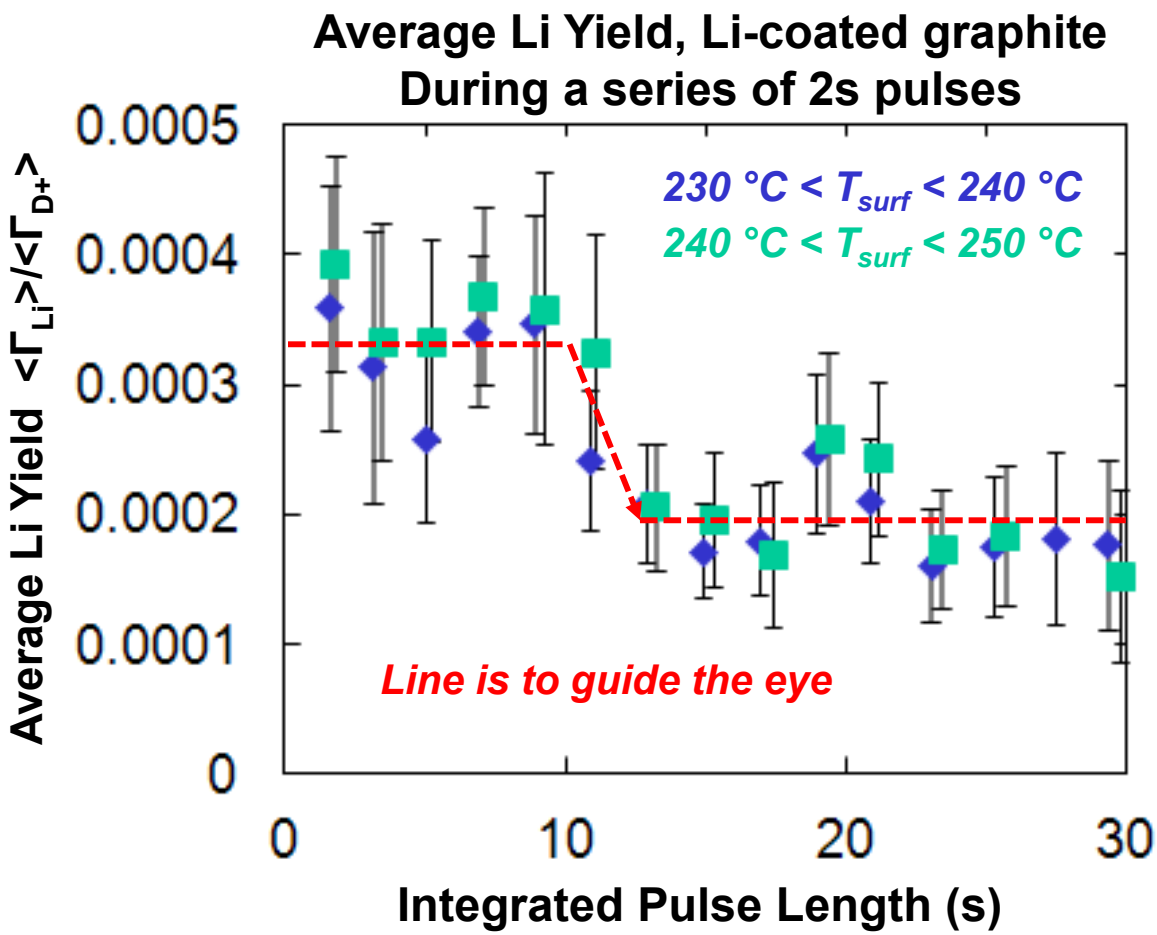


- Neutral plasma vs. ion beam
- 20 eV vs. 300-1000 eV D^+ ions

Li-coated graphite enters "low-yield" regime after significantly less D^+ fluence than Li-coated TZM

- Enters "low yield" regime after ~10-12 seconds **($\Phi_{D+}/\rho_{Li} \approx 300$)**
  - Li-coated TZM: **4300**
- Post-mortem visual analysis of sample confirms Li depletion





Short lifetime of Li coating on graphite not explained solely by low re-deposition fraction

- Assuming zero re-deposition, lifetime $\tau = \rho_{Li} / \langle Y * \Gamma_{ion} \rangle$

Expected Lifetime ≈ **250 s**

Observed Lifetime **≈ 10-12 s**

- Indicates fast diffusion of lithium in graphite may be occurring

$$D_{\perp} = (4.5 \times 10^{-6}\ \mathrm{cm}^2/\mathrm{s}) \exp(-0.26\ \mathrm{eV}/kT)^{*}$$

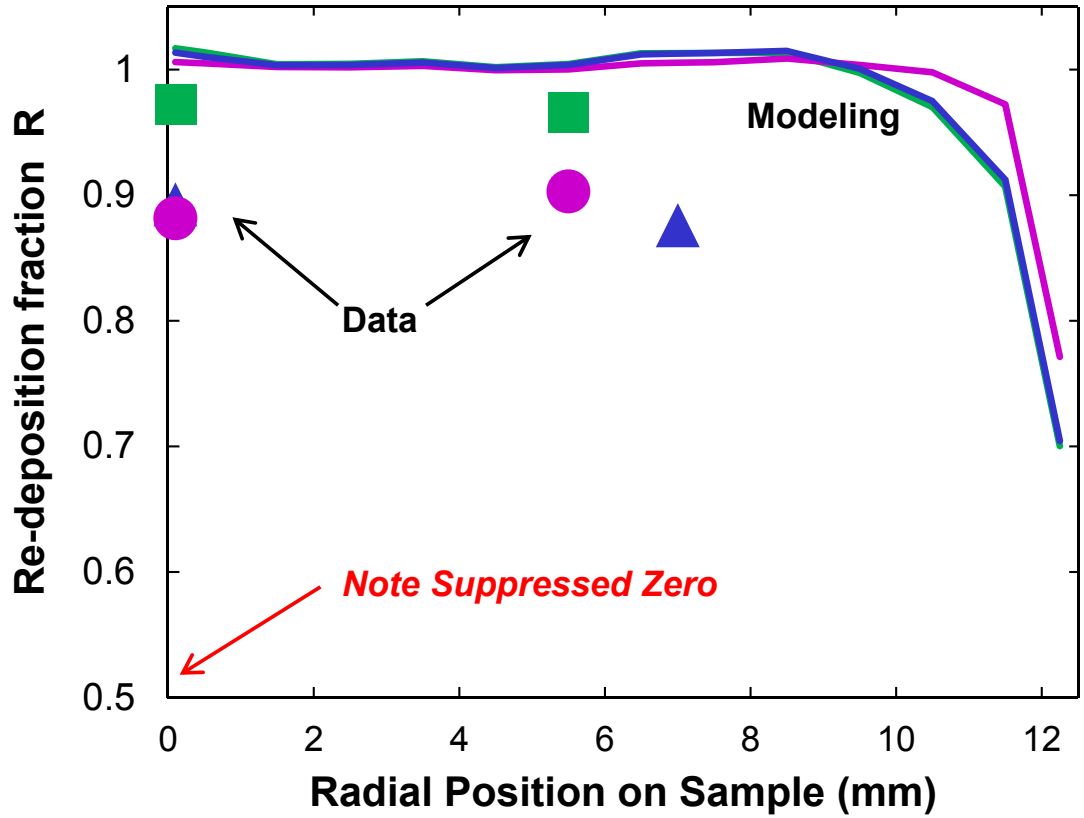
$$\tau_{\mathrm{diff,Li,25^{\circ}C}} \approx \left(\frac{\text{Li thickness (nm)}}{130}\right)^2 \approx \left(\frac{250}{130}\right)^2 \approx 3.7\ \mathrm{s}$$

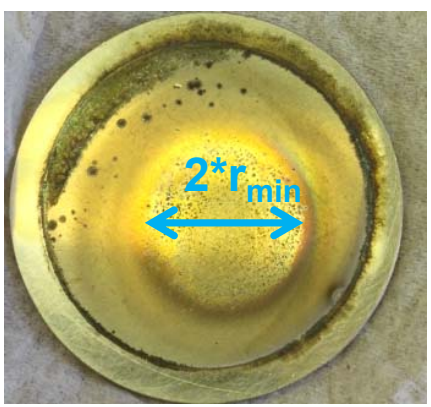
N. Itou et al., JNM 2001

Measured re-deposition fractions for Li-coated TZM Mo are high but below predictions of model

$$\tau = \rho_{Li}/\langle Y \times \Gamma_{ion}\rangle(1-R)$$

- τ(r=0) is time when intermediate regime ends, solve for R
- Determine post-mortem minimum radius r_{min} that still is covered with Li





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Discussion

- Observed Li yields << Langmuir evaporation in vacuum
  - Low-T yields consistent with TRIM sputtering of LiD
  - 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 significantly longer on TZM Mo
- Measured re-deposition fractions 0.85 < R < 0.98
  - Slightly less than predicted by modeling (R > 1.0)
- Transition between "high" and "intermediate" erosion regime warrants further study

Summary

- Re-deposition model was developed to determine lifetime of Li coatings in NSTX-U
- Li coating lifetimes on TZM Mo are strongly extended due to re-deposition fractions $R_{Li} > 0.85$
- Motivates extending model to different elements (B, C, O, etc.) and different geometries (oblique incidence)

Thank you!

- Questions?

Backup Slides

Calibration of Phantom camera measurements

$$\text{Geometry Factor: } f_{geo} = \frac{\pi\left(\text{Radius}_{\text{Objective Lens}}\right)^2}{4\pi(\text{Optical path length})^2}$$

$$= \frac{\pi(2.36\text{ cm})^2}{4\pi * (34.0\text{ cm} + 86.4\text{ cm} + 3.8\text{ cm} + 1.0\text{ cm})^2} = 8.88 * 10^{-5}$$

$$\text{Optical Factor: } f_{optical} = R_{mirror} * T_{window} * T_{filter} = 0.9 * 0.5 * 0.36$$

$$= 0.1215$$

$$\text{Sensitivity of CCD: } S_{CCD} = 22\text{ photons/count}$$

Obtaining Li atoms / photon from modeling

$$\frac{\text{Li atoms}}{\text{second}} = \underbrace{\frac{\text{counts}}{\Delta t_{\text{exposure}}}}_{\text{Measurement}} * \underbrace{\frac{\text{Li atoms}}{\text{photon}}}_{\text{Modeling}} * \underbrace{\frac{S_{CCD}}{f_{geo} * f_{optical}}}_{\text{Calibration}}$$