NSTX-U

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

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DIII-D Boundary PMI/Meeting
General Atomics, San Diego
July 22, 2014

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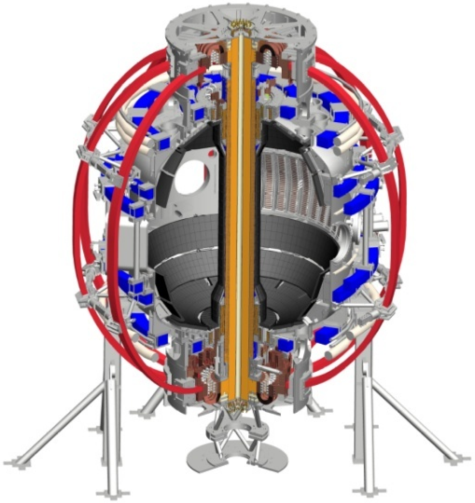

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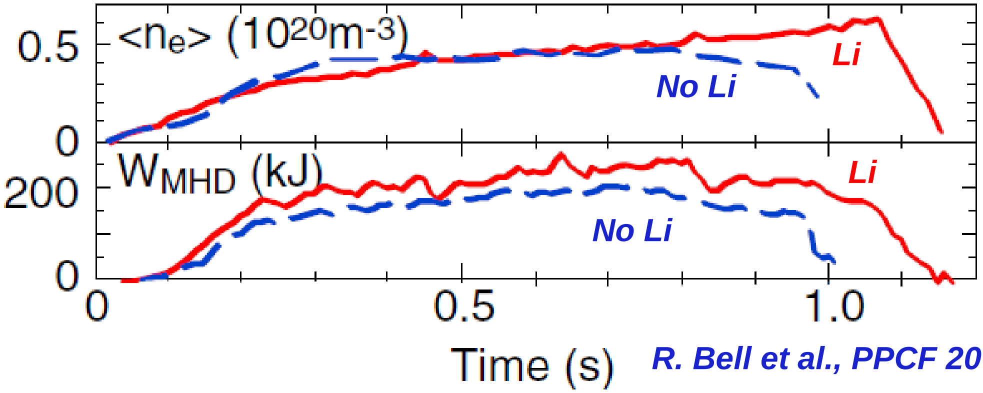
Outline

- **Introduction/Motivation**
- Theory of Li erosion
- Experimental apparatus & procedure
- Results/discussion
- B erosion

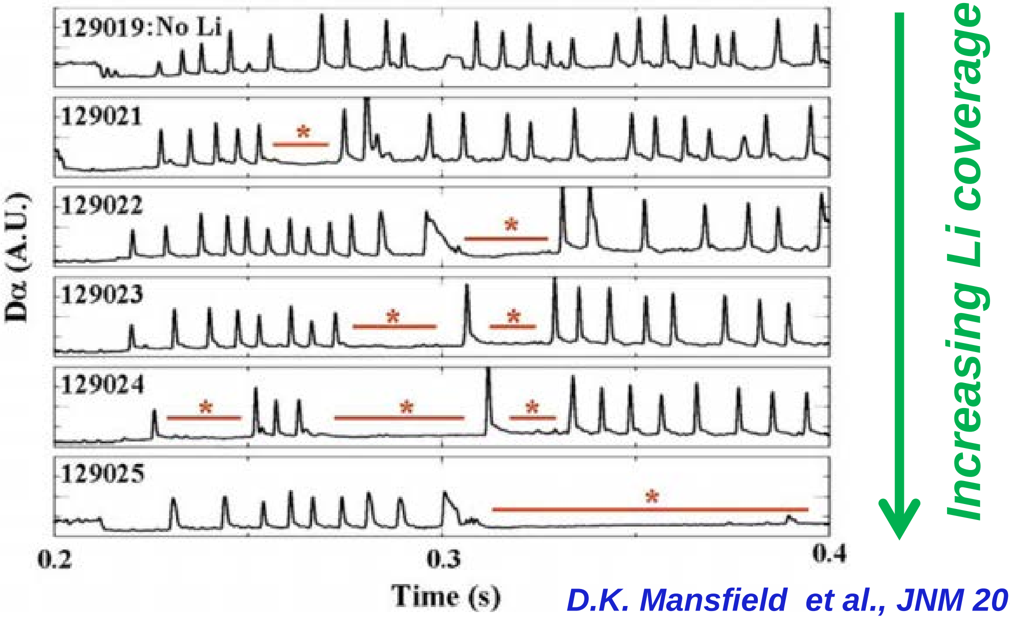
Lithium improves plasma performance and protects underlying substrates

- 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

Li Films in NSTX



R. Bell et al., PPCF 2009



D.K. Mansfield et al., JNM 2009

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[a] *G. Mazzitelli et al., FED 2010*

[b] *T. Abrams et al., JNM 2013*

Previous results on flow-flux devices suggest Li erosion may be unacceptably high at elevated temperatures

- Li erosion rate scales with temperature
  - Evaporation (Langmuir Law)
  - T-dependent sputtering (PISCES-B, IIAX, DIII-D)

- Thermal-spike model[a]:

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

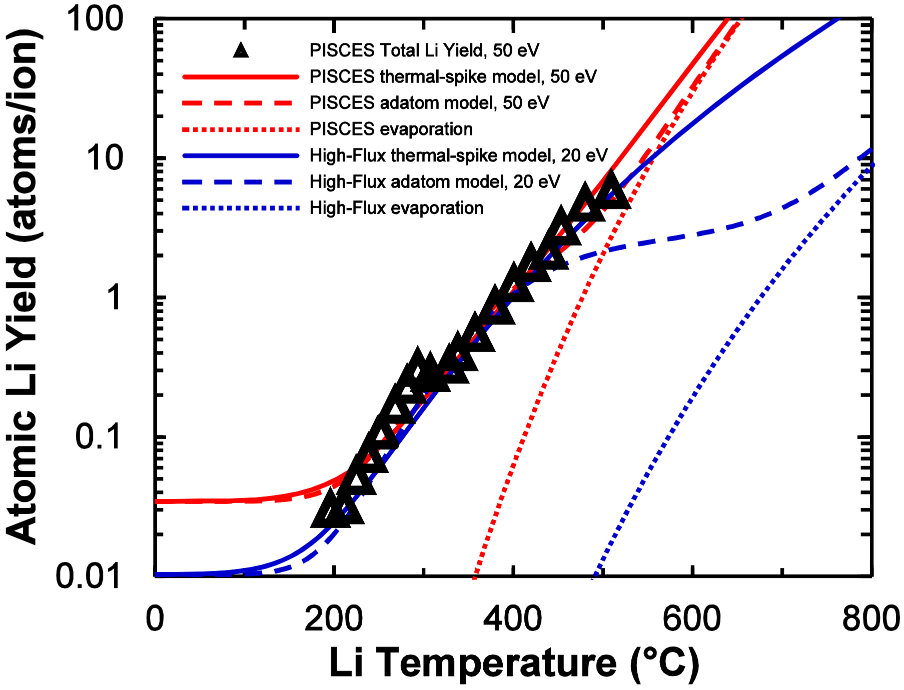
A,B: Fitting parameters
k: Boltzmann's constant

- Adatom-sublimation model[b]:

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

Y_{ad}, A, E_{eff}: Fitting Parameters

Atomic Li Yield vs. Li Temperature Measured on PISCES-B



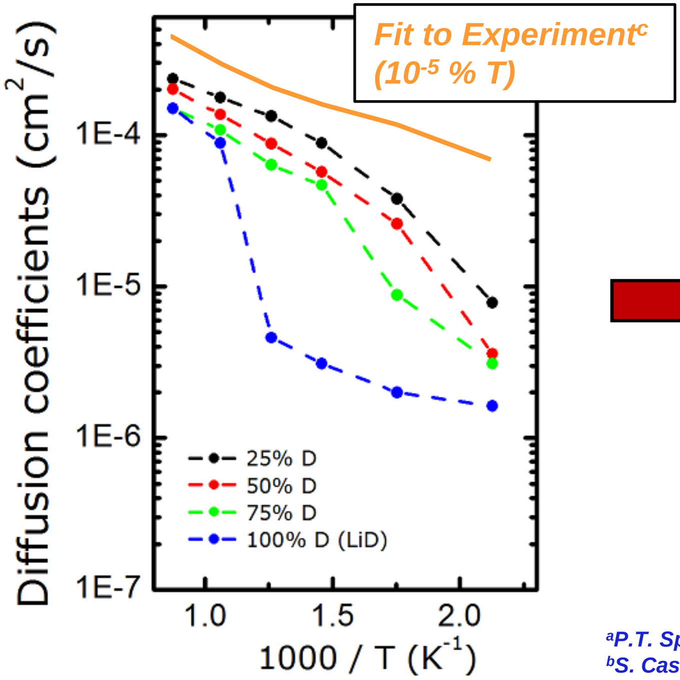
R.P. Doerner et al., JNM 2001

[a] *J.P. Allain et al., Phys Rev B 2007*
[b] *R.P. Doerner et al., J. App. Phys. 2004*

At higher D fluxes and fluence, Li+D mixed-material effects must be accounted for

- Li readily absorbs atomic D, forming LiD[a,b]
  - D will diffuse into Li[c], resulting in D/Li ratios ***β*** up to 1:1[d]
  - D buildup is slow on low-flux devices
  - At high fluxes, D bombards surface faster than Li can absorb it

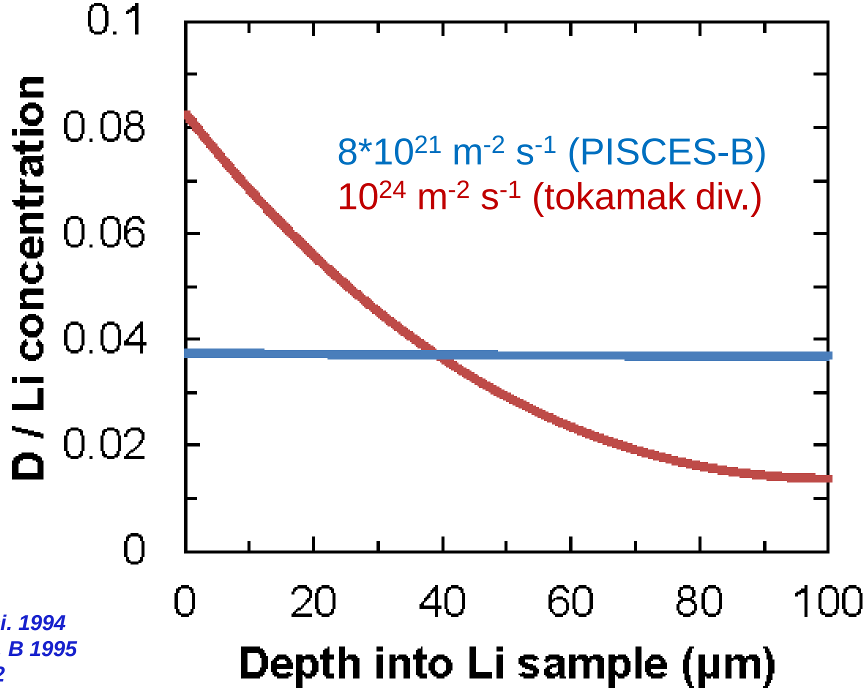
D diffusivity in Li



Fit to Experiment[c] (10^{-5} % T)

M. Chen, unpublished data

D / Li concentration profile after D fluence of 1.6×10^{23} m^{-2}

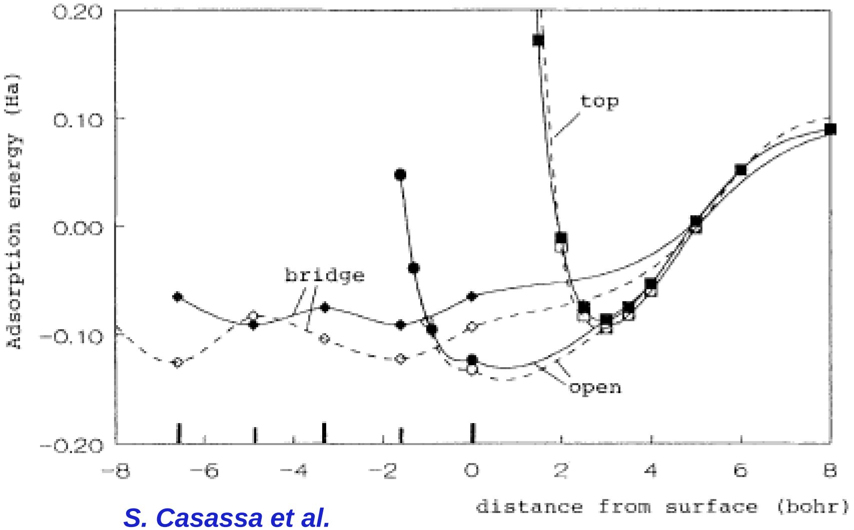


[a] *P.T. Sprunger et al., Surf. Sci. 1994*
[b] *S. Casassa et al., Phys. Rev. B 1995*
[c] *H. Moriyama et al., JNM 1992*
[d] *M.J. Baldwin et al., FED 2002*

Sputtering of LiD is suppressed relative to pure Li

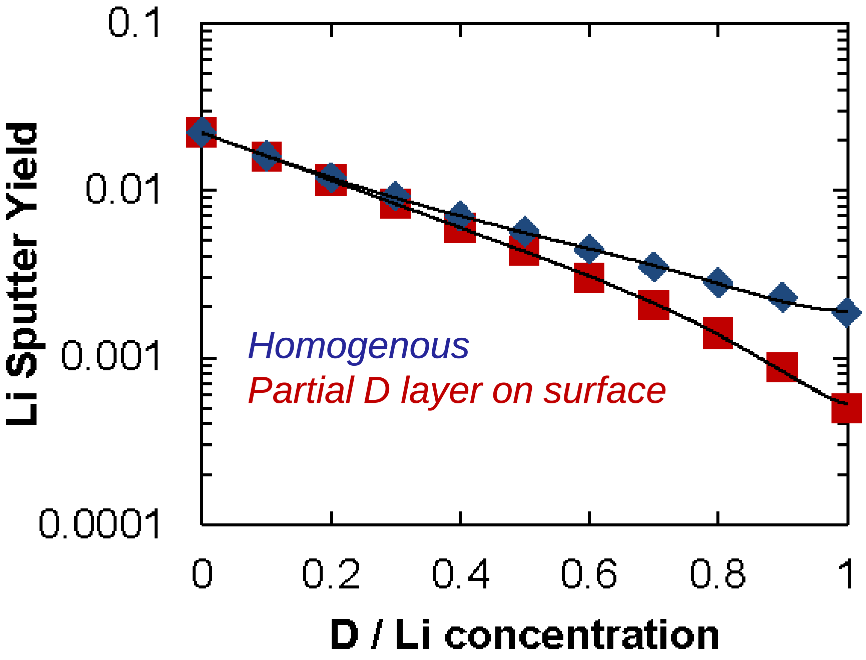
- **Preferential sputtering**: less atoms available to sputter
- **Chemistry**: SBE* is higher for LiD (2.26 eV) vs. Li (1.67 eV)

Three stable positions for D atoms at a Li surface:



S. Casassa et al.

SDTrimSP simulations of $Y_{Li,LiD}$ vs. D/Li fraction



*Assumed equal to heat of sublimation

Evaporation of LiD in suppressed relative to pure Li

- Li vapor pressure above Li/LiD mixtures is reduced relative to pure Li

- Reduction factor is independent of temperature

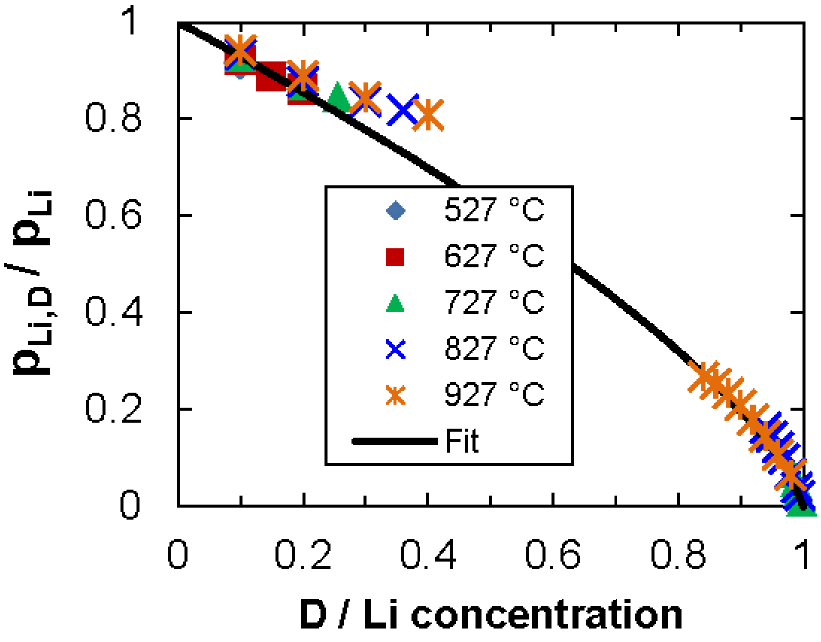
$$\Gamma_{\mathrm{evap}}(T_{Li}) = \frac{p_{Li,D}}{\sqrt{2\pi m_{Li} k T_{Li}}}$$

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

- Empirical fit formula:

$$\frac{p_{Li,D}}{p_{Li}} = (1-\beta)^{0.705}$$

Mixed-material Li/LiD vapor pressure vs. pure Li



E.E. Shpil'rain et al., 1987

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

$$\Gamma_{Li}(T_{\mathrm{Li}},\beta,\Gamma_{D+}) = \Gamma_{D+}\left[Y_{\mathrm{coll}}(\beta)+\frac{Y_{ad}(\beta)}{1+A\exp\left(\frac{E_{eff}}{k_B T_{Li}}\right)}\right]+\frac{p(T_{Li},\beta)}{\sqrt{2\pi m_{Li} k_B T_{Li}}}$$

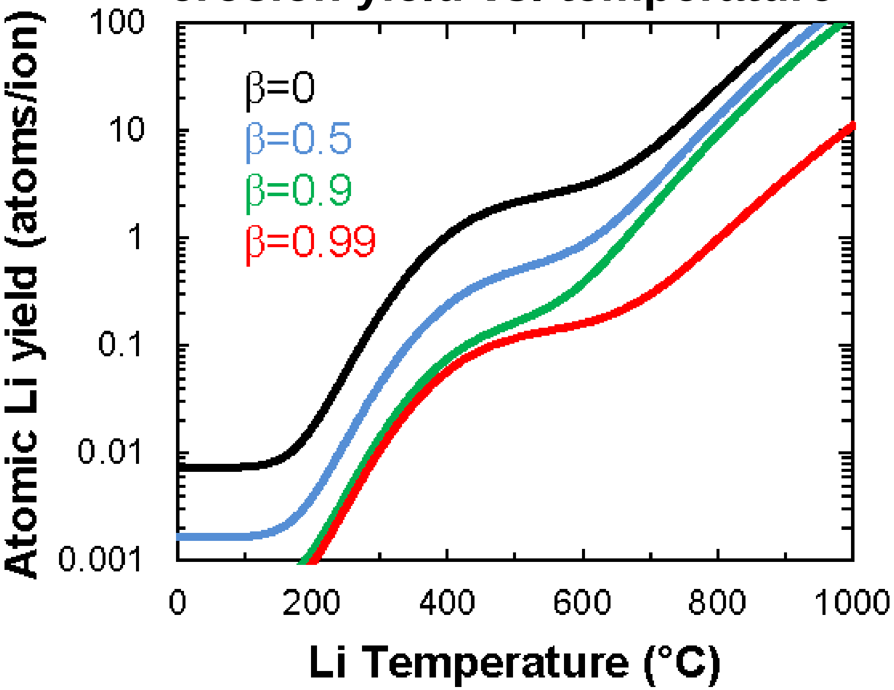
Total Li erosion ($m^{-2}\ s^{-1}$)

Collisional (BCA) sputtering

Thermally-enhanced sputtering

Evaporation

Mixed-material Li/LiD erosion yield vs. temperature



- **Adatoms** are excited from their bound states, but not with sufficient energy to sputter
- Adatoms on a liquid?
  - Have been observed in MD simulations[a]
  - *A* is related to adatom lifetime τ
  - $\tau_{\mathrm{Li}} >> \tau_{\mathrm{Be}}$ (less vacancies on liquid)
- Y_{ad}/Y_{coll} is fairly constant on different materials[b,c]

[a] *K. Nordlund etl al. Lett. Nat. 1999*

[b] *R.P. Doerner et al., J. App. Phys. 2004*

[c] *H. Gades et al., Phys. Rev. B 1994*

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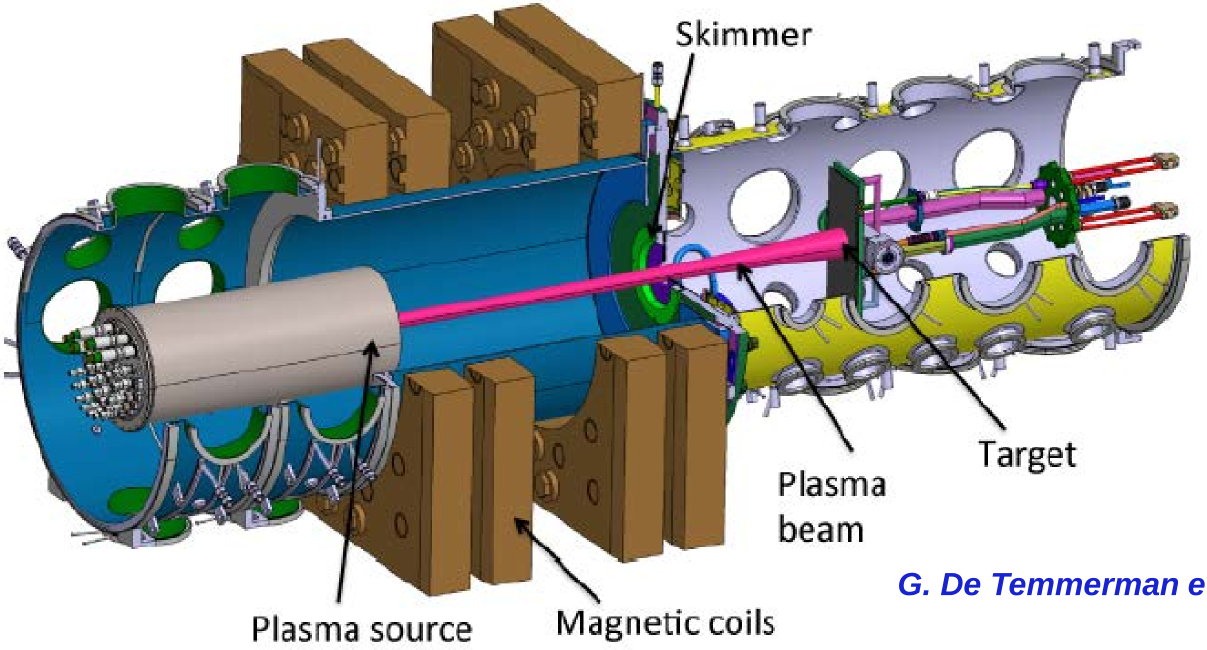
Model tested and analyzed in Magnum-PSI linear plasma device

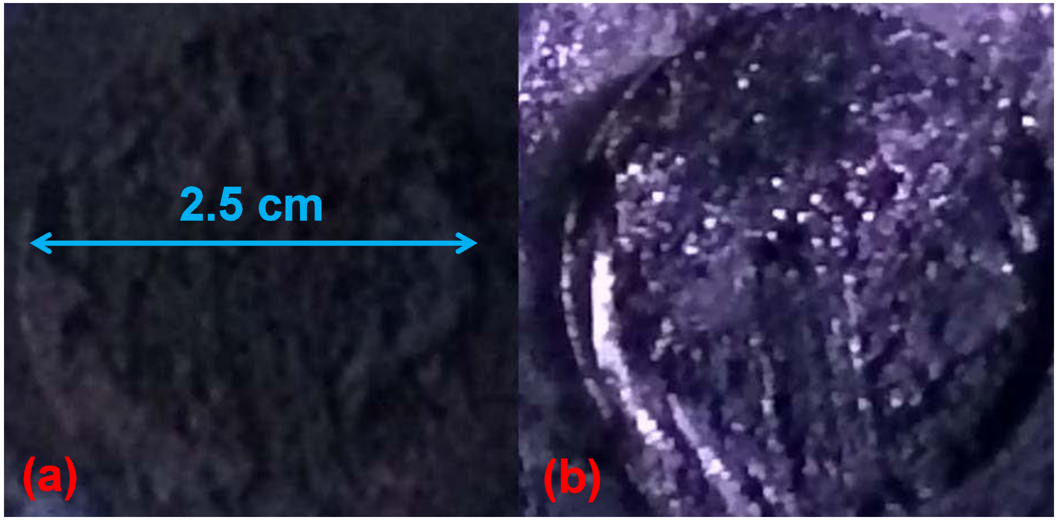


G. De Temmerman et al., FED 2013

- $\Gamma_{D+} \lesssim 2{*}10^{24}\ \mathrm{m^{-2}s^{-1}}$, $T_e \lesssim 3$ eV, $n_e \lesssim 8{*}10^{20}\ \mathrm{m^{-3}}$
- 5-10 s pulses, B = 0.25 T at target
- Normal incidence: no magnetic pre-sheath
- Two sample types (both 2.5 mm diameter)
  - Evaporated Coatings ($\leq$ 1 μm)
  - Shallow Li cups (0.1 – 1.0 mm)

New procedure developed for loading 0.1-1.0 µm thick Li targets in Magnum-PSI sample holder

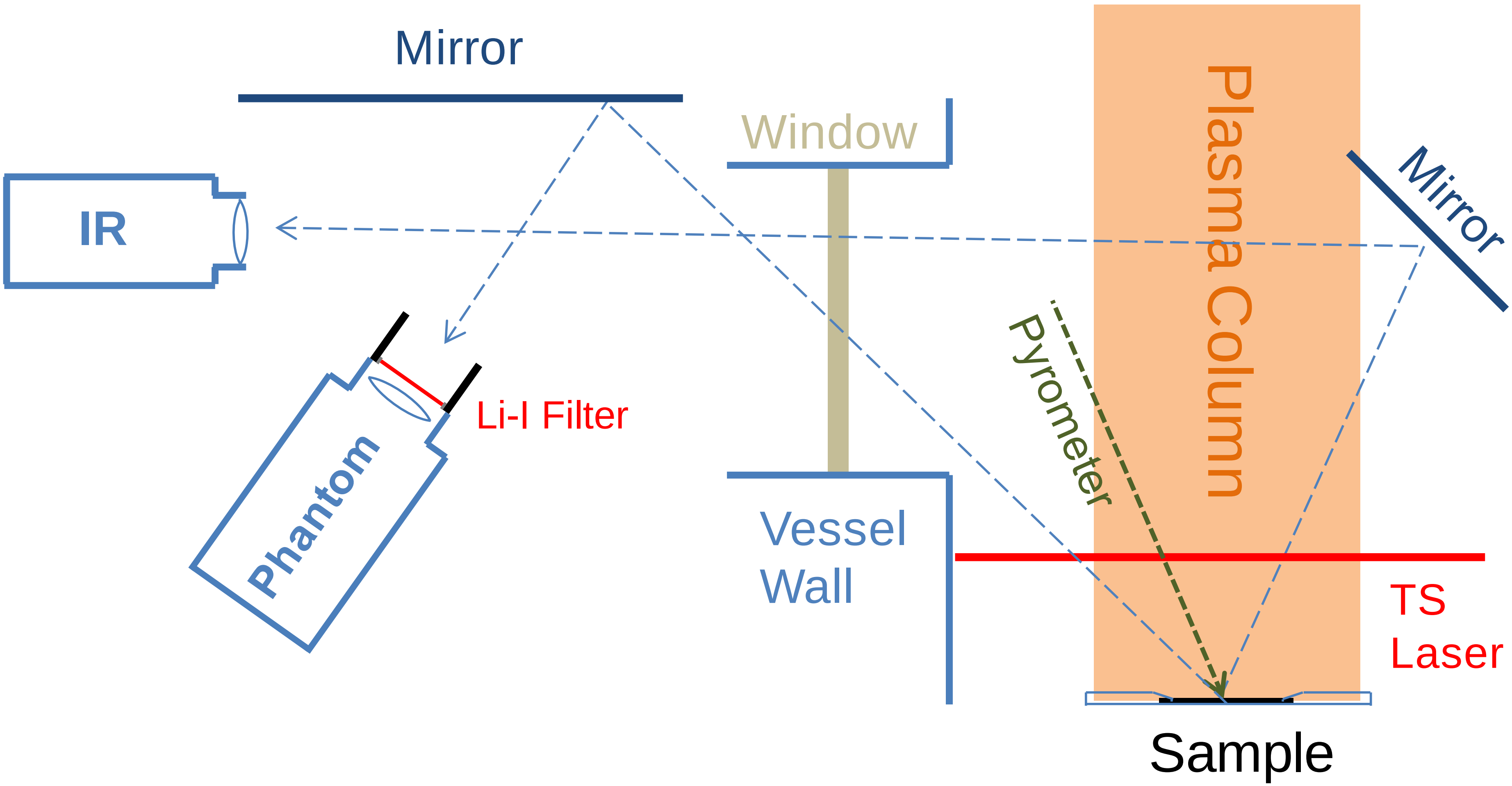
1. Li melted into sample wells inside Ar glove box
2. Sealed with SS shim stock covers & heat-seal mylar bags
3. SS cover remained on sample during mounting
4. Li exposed to atmosphere for 20-30 s between cover removal & vessel pumpdown
5. Ar plasma discharges used to remove oxide coating from Li



Photograph of Li sample before (a) and after (b) Ar plasma discharge cleaning.

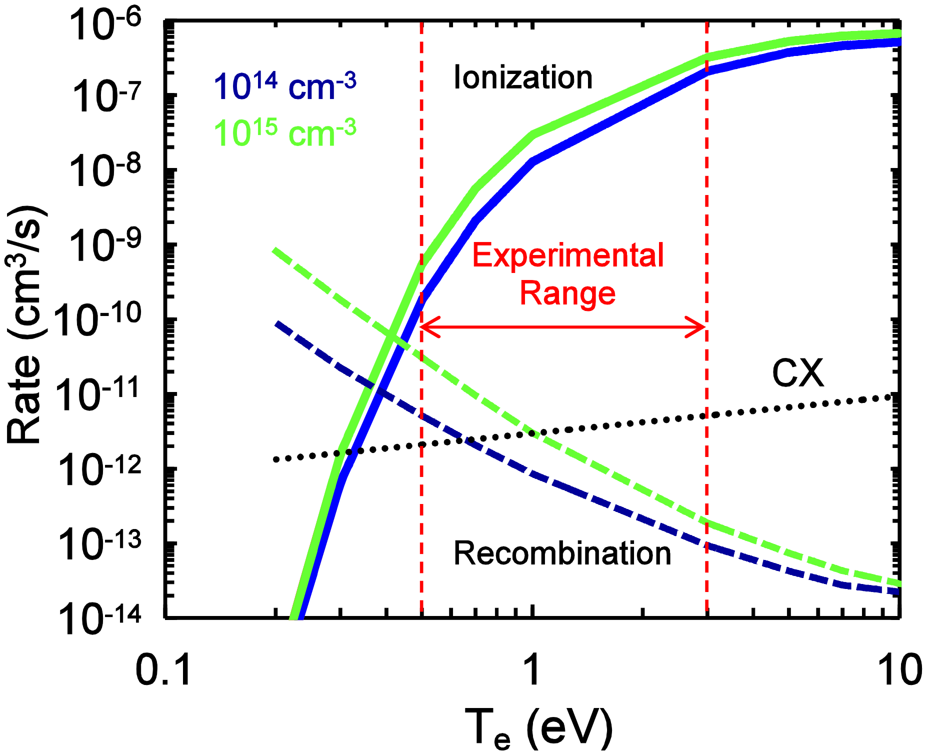
Li surface transformed from dark to shiny.

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



Li-I emission rates can be interpreted using atomic data from ADAS collisional-radiative model*

- Approximations:
  - Steady state ($t_{\mathrm{ionize}} \sim 1\ \mu s$)
  - No recomb./CX
  - No ⊥ impurity transport
  - No secondary elect. emission
  - No radiation trapping



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

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

Li yields inferred from Li-I emission measurements

- Solve Li^0 continuity equation with boundary condition:

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

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

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

Ionization rate coefficient (ADAS)

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

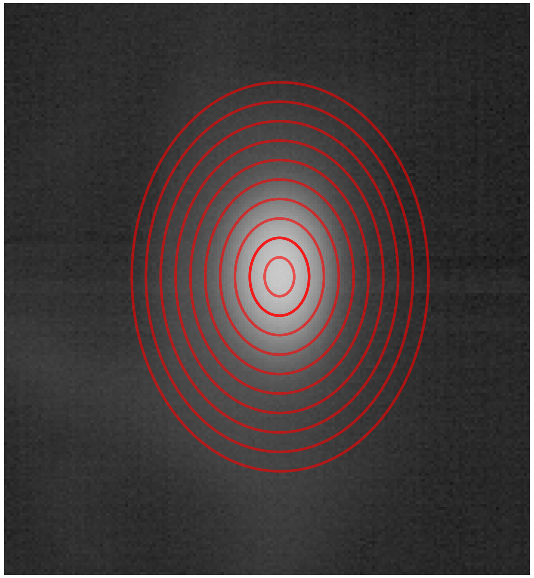
Photon emissivity coefficient (ADAS)

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

- 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}**



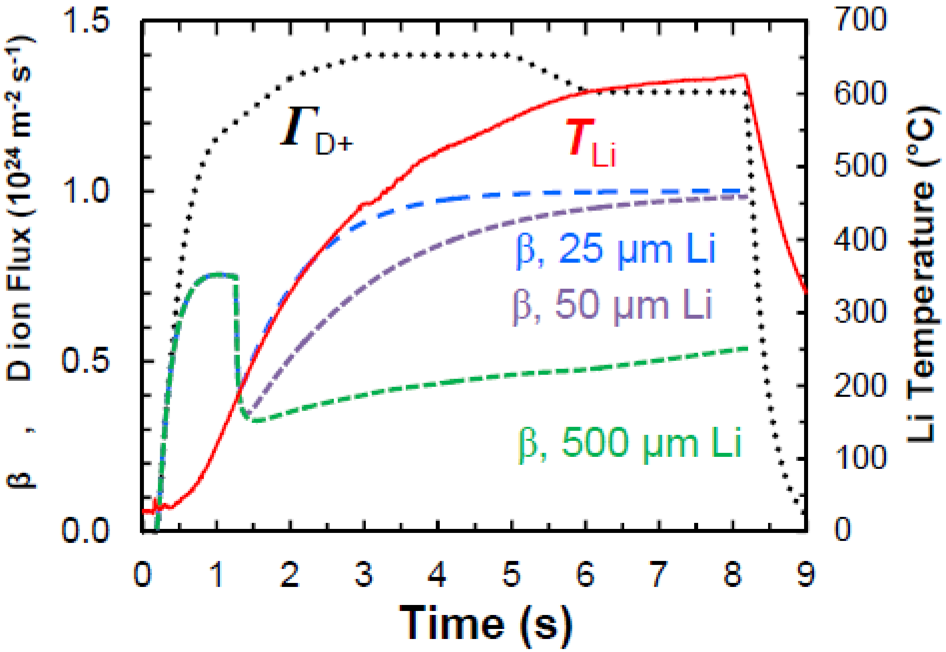
Axially average Li-I emission

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
   - Significant melt motion led to uncertainty in time evolution of Li thickness
   - Time evolution of β for various thicknesses were tested

Time Evolution of β, $\Gamma_{\mathrm{D+}}$, and T_{Li} during typical Magnum-PSI discharge



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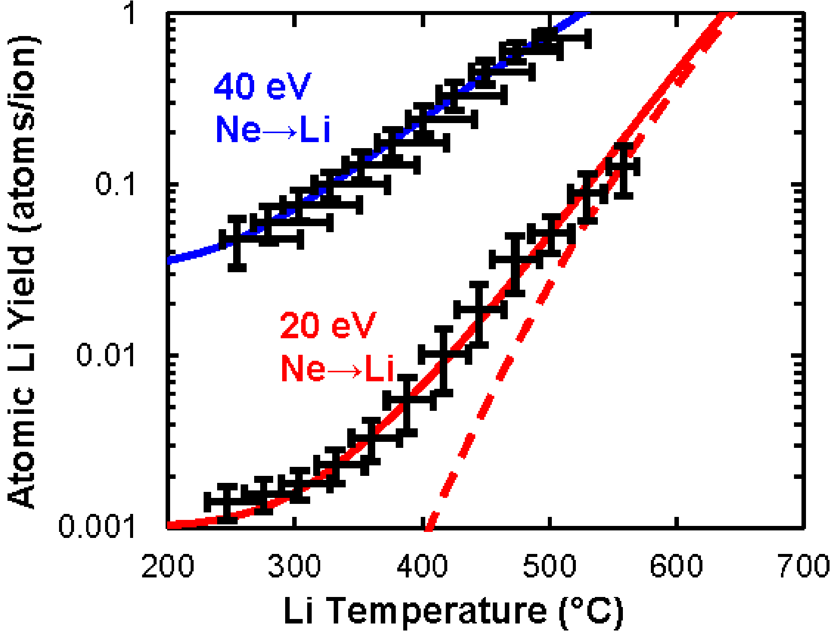
Li yields measured during Ne plasma bombardment are greater than Langmuir Law evaporation

- Suggests erosion model is valid for H-free Li films

- 20 eV Ne→Li erosion much lower than 40 eV
  - Model predicts T-dependent sputtering is independent of E_{Ne+}
  - Possible near-threshold effects for Ne

- 40 eV Ne →Li consistent with previous results for He →Li

Atomic Li Yields Γ_{Li}/Γ_{Ne+} vs. Li Temperature



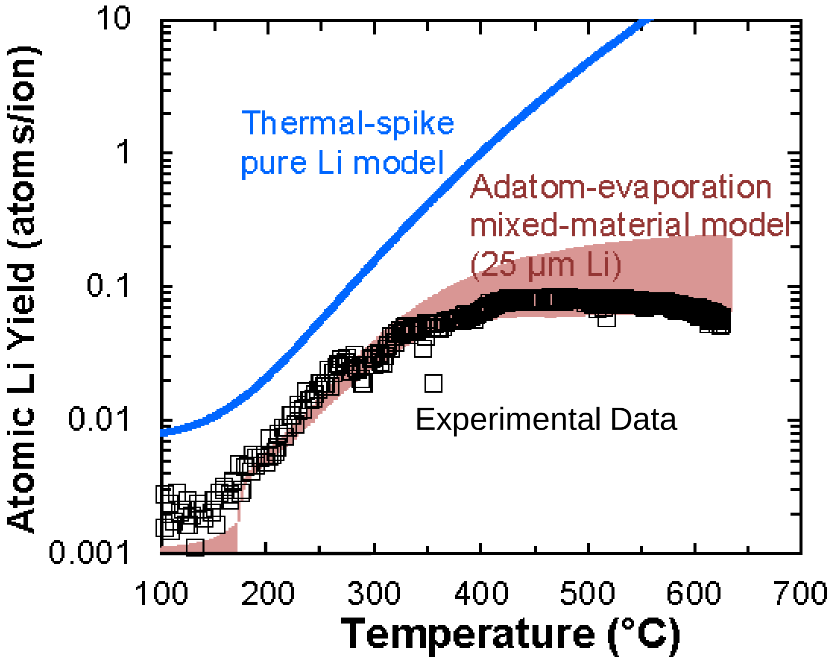
Solid line: Thermal-spike or adatom model (indistinguishable)
Dashed line: Evaporation only
Error bars: Experimental measurements

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

- Error band is distance between homogenous & partial D monolayer surface models

- Adatom mixed-material model captures quantitative evolution of Li erosion rate
  - *A priori* assumption that Li thickness reduced to ~25 μm
  - Data is most consistent with D monolayer on surface model (bottom of error band)

Atomic Li Yield Γ_{Li}/Γ_{D+} vs. Li Temperature



Numerous physics possibilities have been considered

- Recomb./CX small, but would imply an even lower yield
- Γ_{D+} measured fairly constant 4.0-20 mm from target
- Drifts are almost entirely in azimuthal direction
- Results insensitive to v_{Li} (strong ionization)
- Transmission of optics measured before/after experiments
- Self-sputtering is small, would also imply even lower yield

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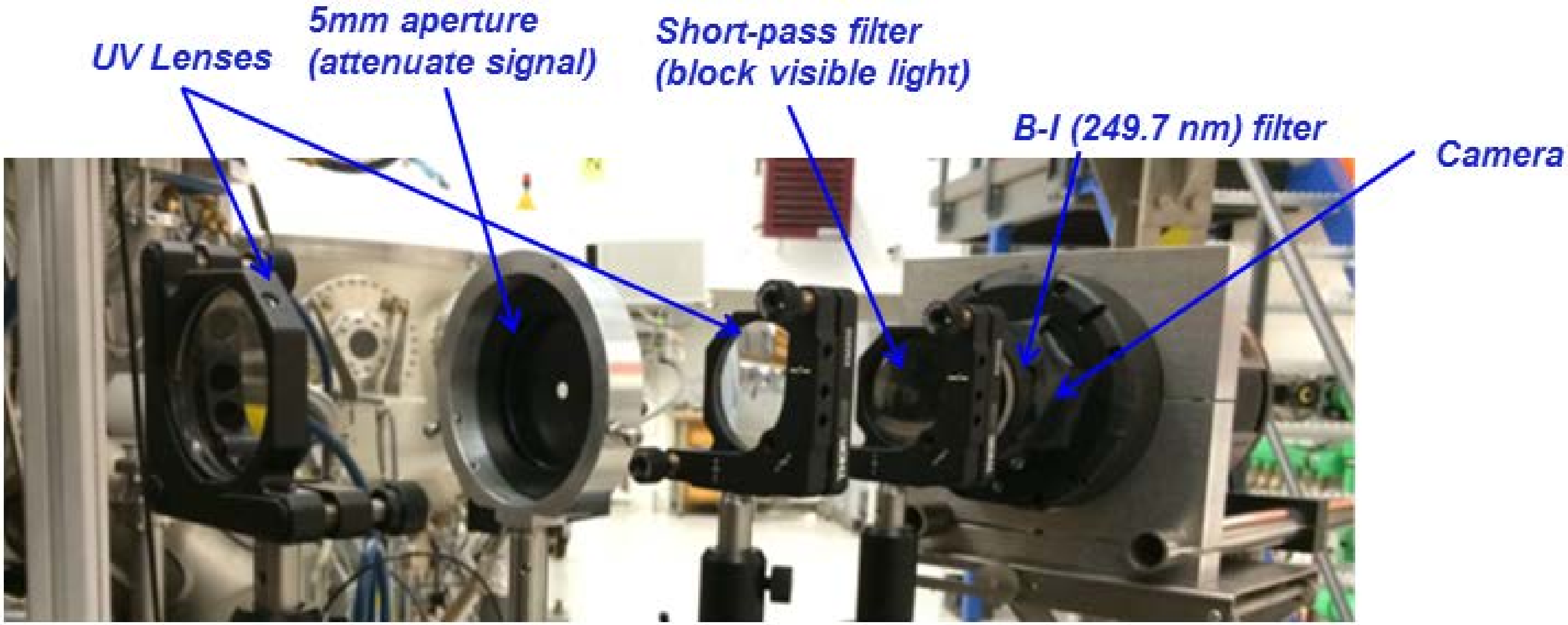
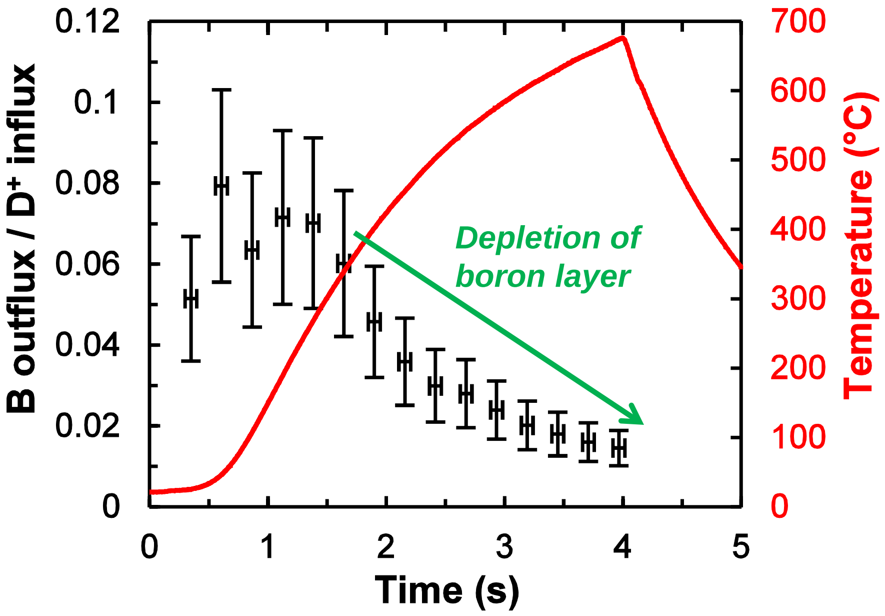
Preliminary measurements of boron erosion under high-flux D plasma bombardment have also been performed

- 300 nm B layers sputter-coated on TZM Mo
- No strong B lines in visible: use **249.7 nm** line
- Imaged with PIXIS 2040-B camera, ~4 Hz, 1 mm^2 res.
- Similar analysis applied to data using ADAS tables



Preliminary measurements of boron are significantly higher than on ion- beam experiments

- $\lambda_{iz,B} >> \lambda_{iz,Li}$
  - "Smearing" of erosion data
  - Can capture total B outflux w/o spatial resolution



- No T dependence observed, but not expected until > $0.5*T_{melt}$[a,b]

[a] R.P. Doerner et al., J. App. Phys 2004
[b] H. Maier et al., PSI 2014

- Y_B >> previous measurement on ion beam device (0.004) and SDTrimSP predictions (0.005)
  - SBE of sputtered coating may be lower than bulk B
  - ADAS ionization rate coeffs. for boron are not n_e-dependent
  - Measured erosion rate consistent w/ depletion after 1-2 s

Conclusions

- Adatom-evaporation mixed-material model developed to predict temperature-dependent Li+D erosion rates
- Techniques for inferring time and spatially dependent erosion yields developed using ADAS atomic phys. data
- Erosion yields of Li and B coatings on TZM Mo measured during high-flux bombardment on Magnum-PSI
- Model captures quantitative dependence of Li erosion yield for thick mixed-material Li/D layers
- B erosion measurements using B-I emission performed for the first time using custom-built optics system

Thank you!

- For more information:
  - "Erosion of lithium coatings on TZM molybdenum and graphite during high-flux plasma bombardment." T. Abrams et al., Fusion Eng. Des. (2014), dx.doi.org/10.1016/j.fusengdes.2014.06.005
  - "Suppressed gross erosion of high-temperature lithium films under high-flux deuterium bombardment." T. Abrams et al., J. Nucl. Mater., under review.
  - Upcoming APS Presentation, Ph.D. Thesis