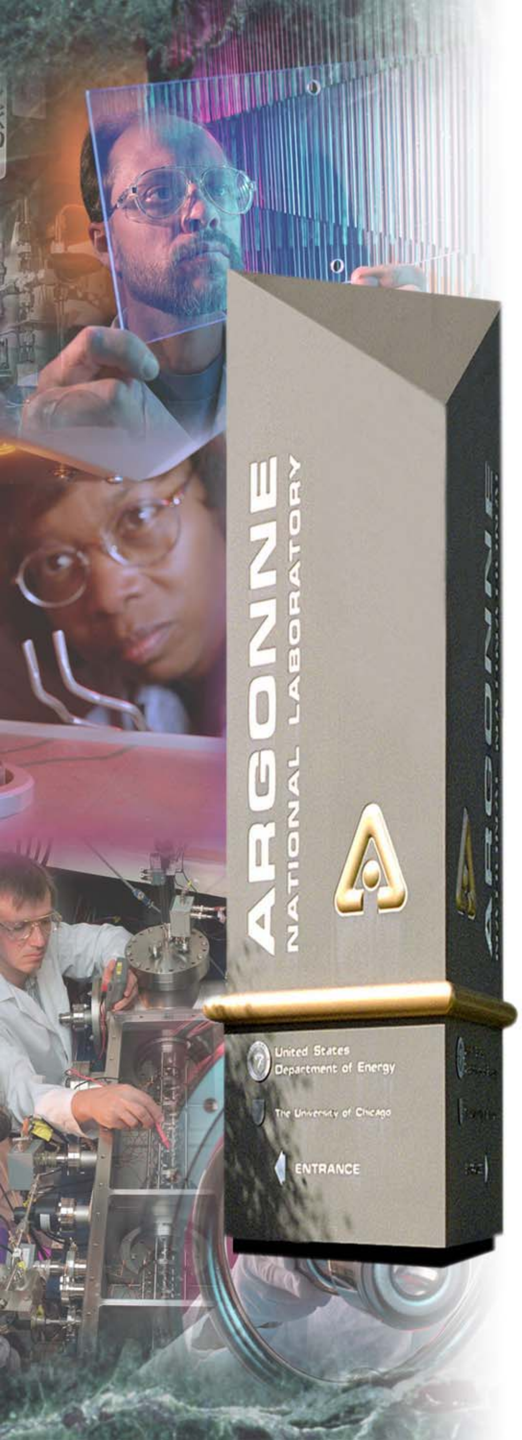

Liquid metal sputtering data/models & DIII-D DiMES analysis

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Liquid metal sputtering data/models & DIII-D DiMES analysis

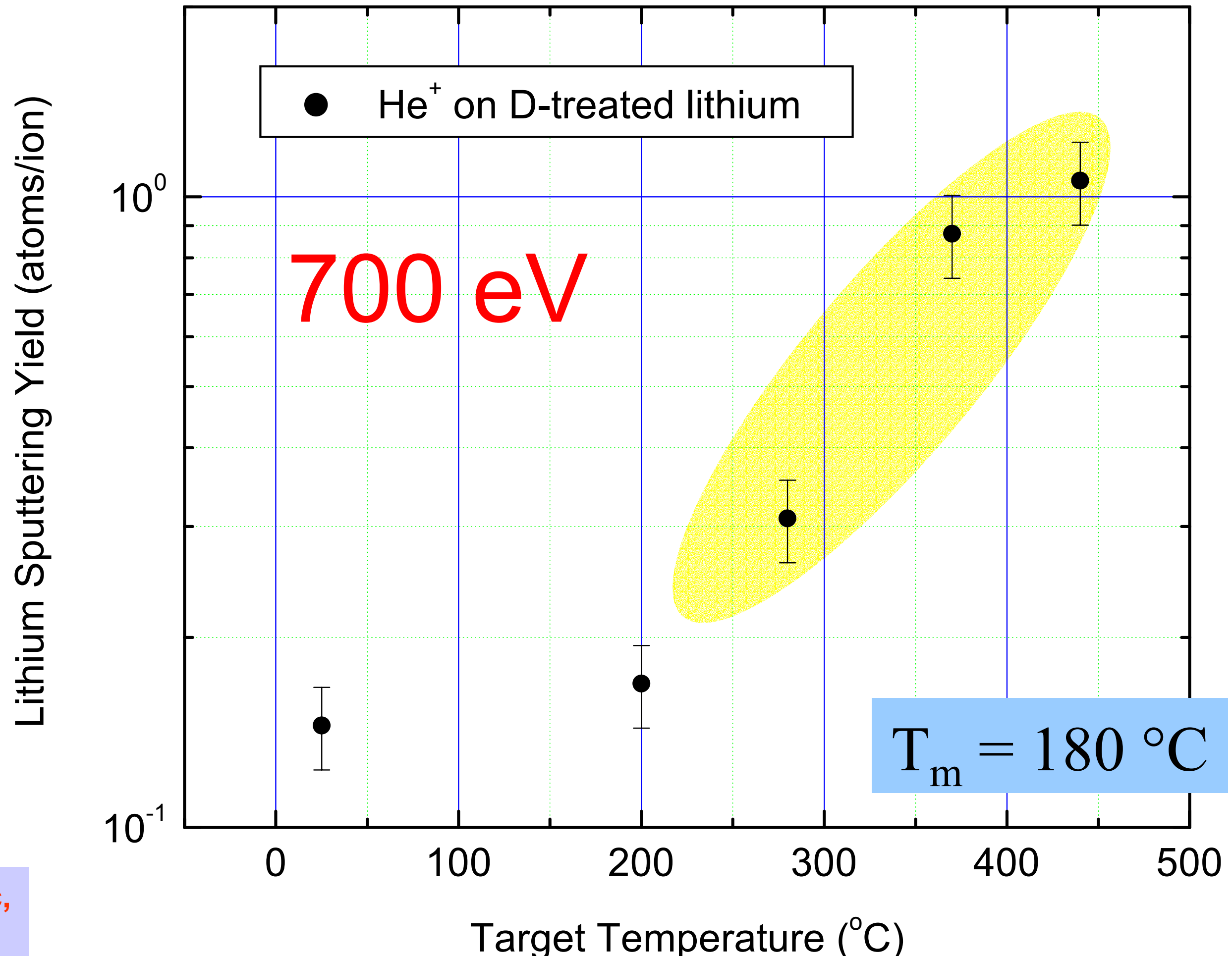
- Lithium erosion mechanisms: Models and Data
- NSTX Low and High-power cases: sputtering
- Quiescent plasma Li-DiMES experiments: erosion
- Measurements on ionization and sputtered Li velocity distributions
- Modeling of physical sputtering
- Erosion/redeposition analysis with WBC/REDEP
- Conclusions

What we know about liquid-metal surface mechanisms

- No significant difference in sputtering from the solid to liquid state when temperature is near melting point
- Non-linear increase in sputtering from liquid-metal when temperature is about 50% higher than melting point (accounting for evaporation)
- Two-thirds of lithium sputtered particles are in the charged state
- Implanted hydrogen leads to a ~ 40% decrease in *lithium* sputtering
- High retention of hydrogen in liquid lithium (PISCES-B results)

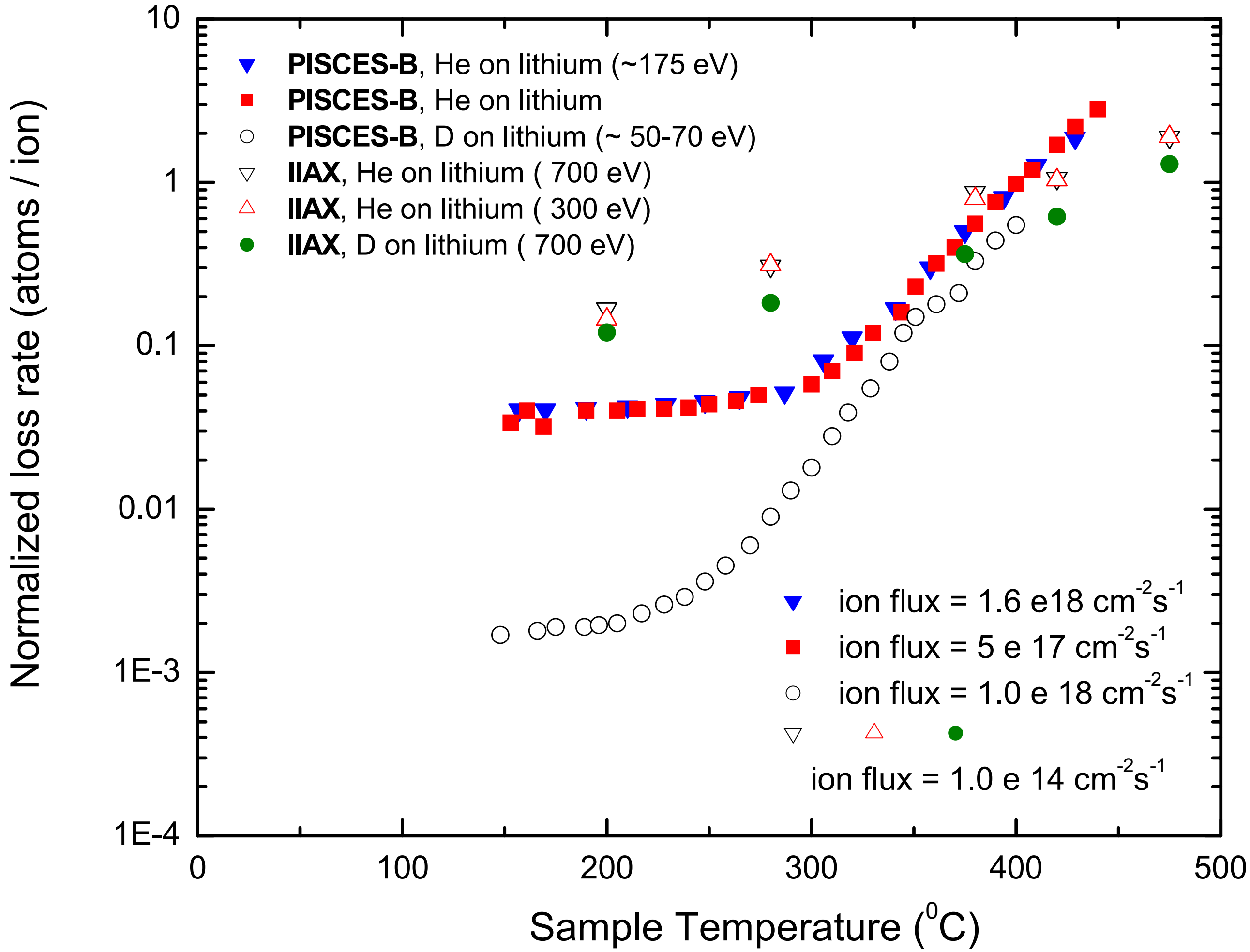
IIAX data on lithium sputtering yield temperature dependence from oblique He^+ bombardment

- Enhanced erosion of lithium measured for temperatures higher than melting temp. for lithium, tin-lithium and tin
- Ad-hoc models for liquid lithium with smooth surface in VFTRIM-3D suggest several temperature-dependent mechanisms[1] are important

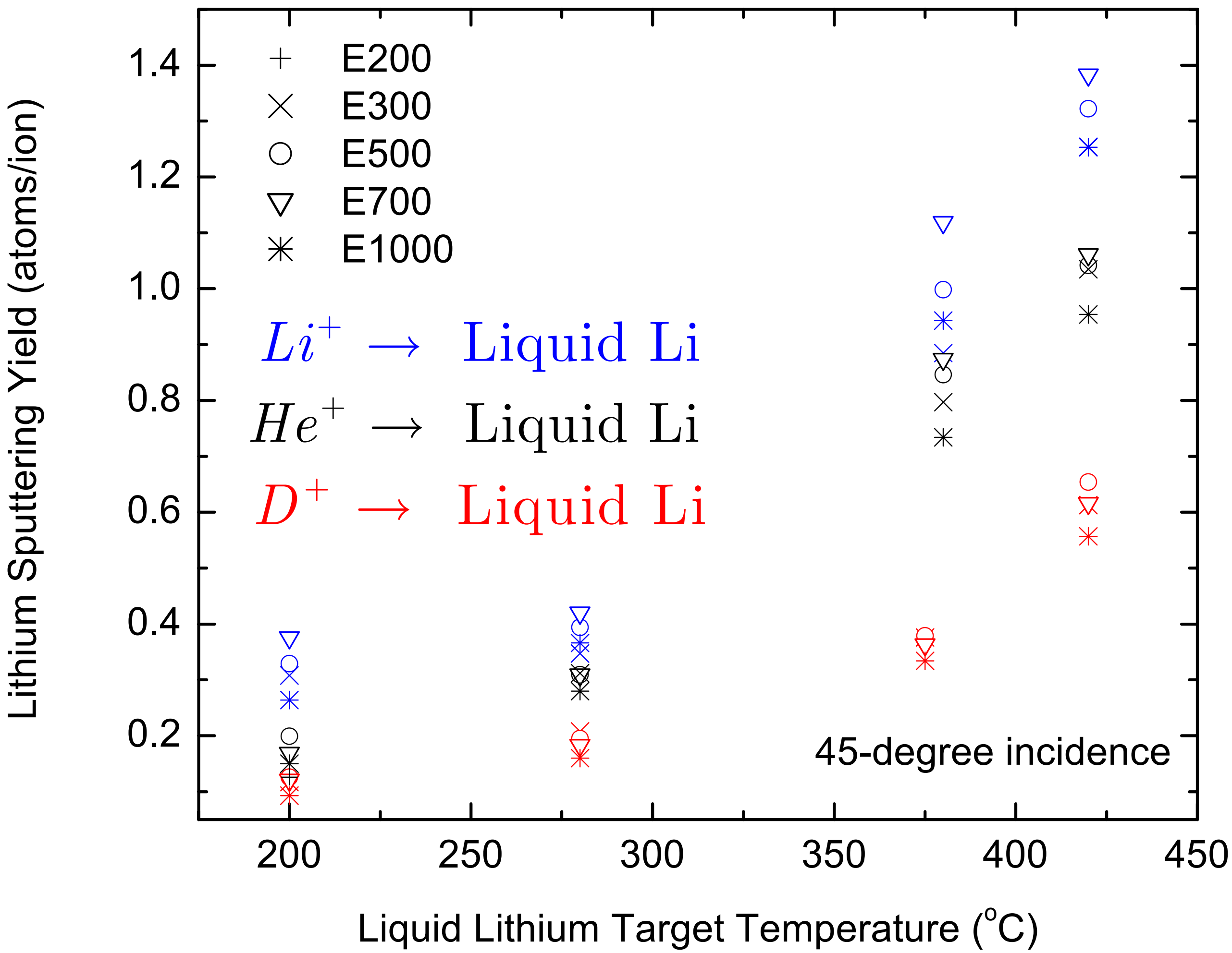


1. J.P. Allain, M.D. Coventry, D.N. Ruzic, J. Nucl. Mater. 313-316 (2003) 645

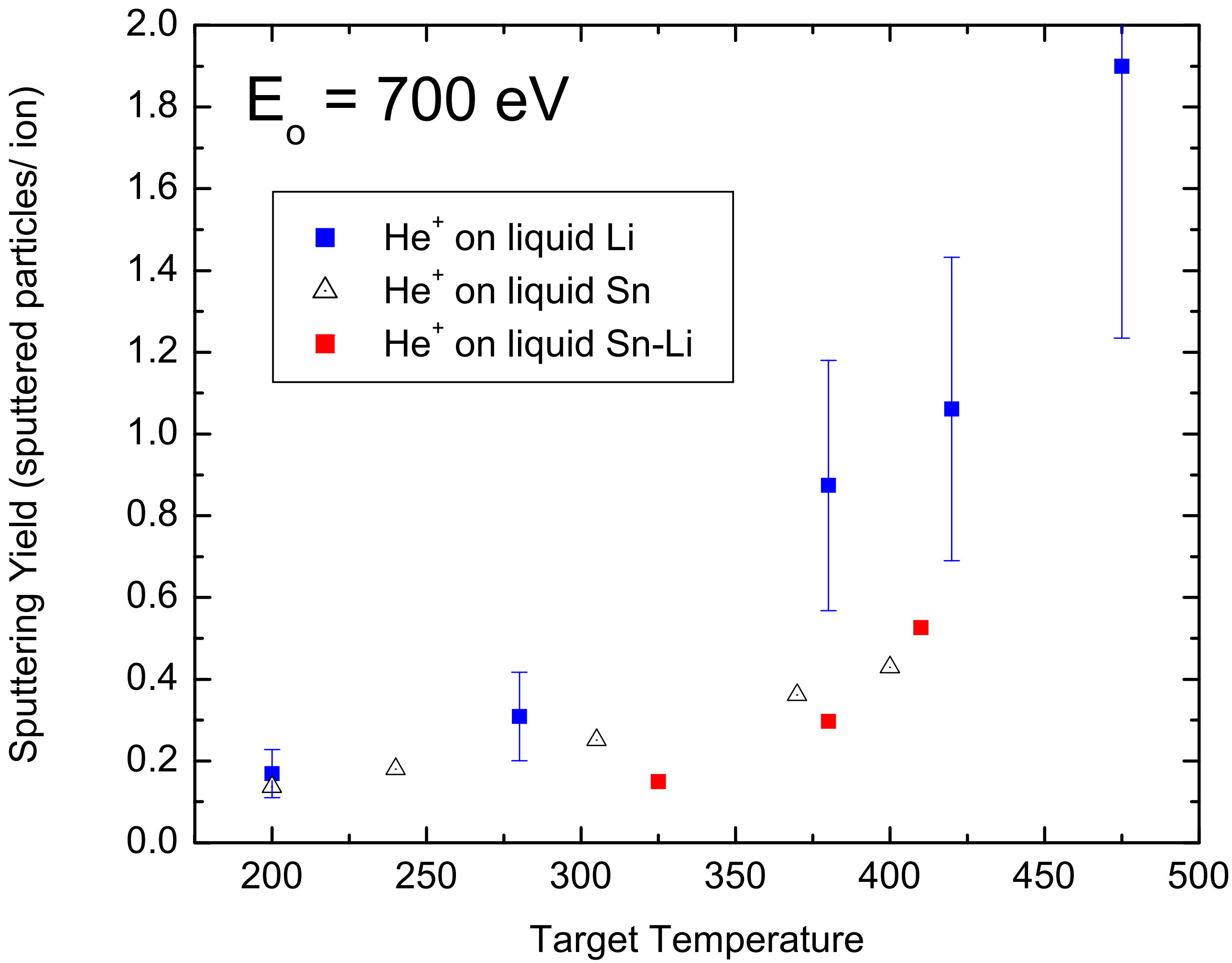
Lithium erosion enhancement measured in various experiments



IIAX temperature-dependent yields for various incident particle energies



Comparison of Sn sputtering with SnLi and Lithium from He^+ bombardment



Liquid-metal erosion mechanisms

- Near-surface energy deposition to "weakly-bonded", mobile lithium atoms lead to non-linear erosion even for low-incident particle energies
- True for materials with low cohesiveness and sublimation heat such as: alkali metals or the alkaline earths, others: Ga, In, Sn, Sn-Li
- In addition, the nature of the binding of the sputtered atom relative to its nearest neighbors and how this changes with system temperature is important to explain the measured enhancement
- Surface stratification (characteristic of liquid-metals) could in fact play a role in the enhancement of erosion

Other possible mechanisms responsible for erosion enhancement

- **Formation of surface adatoms with lower binding to surface (Doerner, et al.)**
- **Bubble formation of implanted He or D could precipitate into nano-size bubbles reaching the surface and emitting a non-linear amount of material**
  - Need more experiments to determine the role of bubble formation on the *enhancement* of lithium erosion in a $\Delta T \sim 200\ ^\circ C$ window.
- **Localized rise in temperature (in the form of thermal or elastic spikes) could lead to a larger Li yield due to its low vapor pressure (a rise of 200 ° C could do this)**
- **Other models for liquid metals?... fluid dynamics model of sputtering?**
  - **M.M. Jakas, E.M. Bringa, R.E. Johnson, Phys. Rev. B 65 (2002) 165425-1**

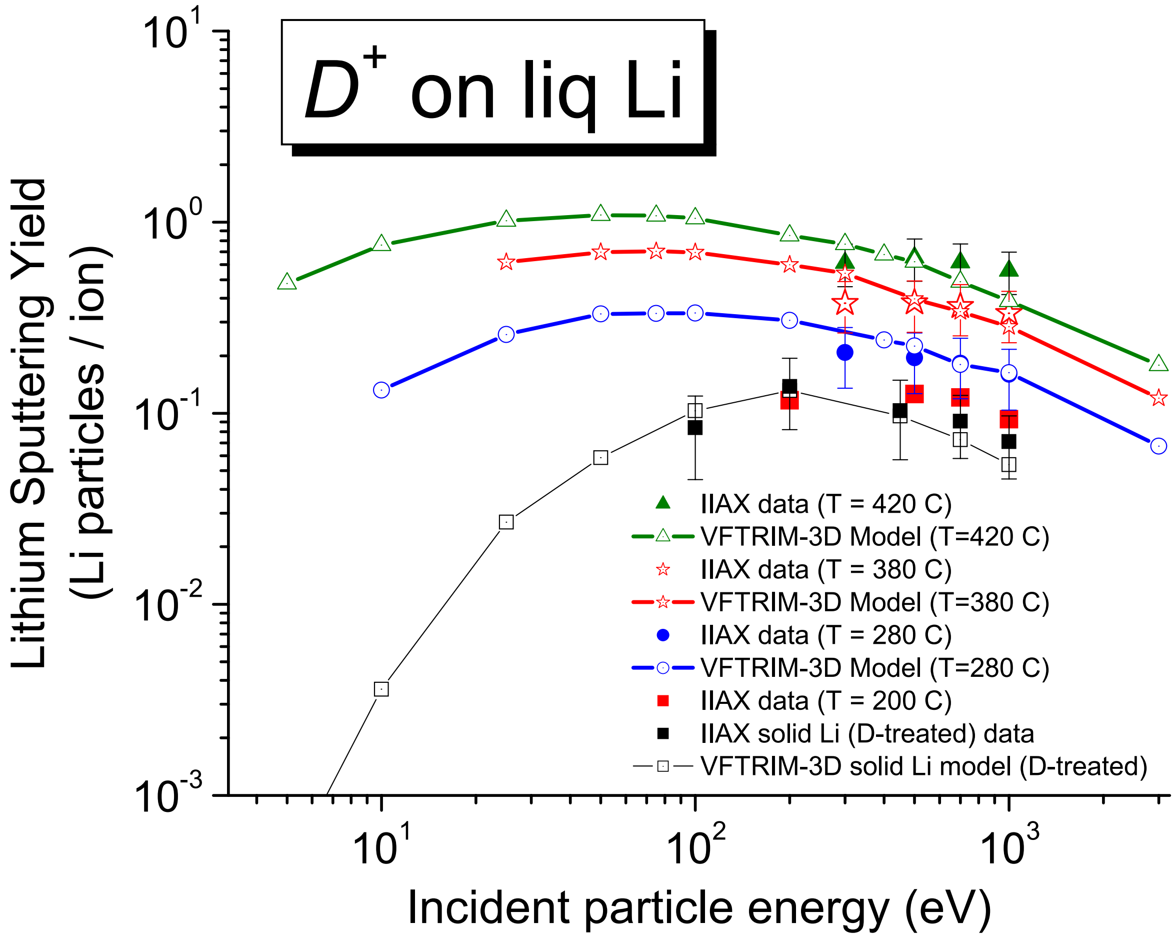
Temperature-dependent Liquid Lithium Models

- **Radiation Activated Adatom Sublimation (RAAS) model (Doerner, et al.)**
  - Assumes adatom formation on a liquid surface and obtains activation energy from MD modeling
  - Scales erosion to incident flux
- **Allain-Ruzic model**
  - Utilizes near-surface spatial distribution of energy cascade from MD models
  - Can predict temperature dependence of erosion
- **Other models**
  - Sigmund, Vaulin, others with: $Y(T) = A*T^{-1/2} \exp(-B/T)$

Empirical Y(T) model (Allain) for NSTX erosion/redeposition studies

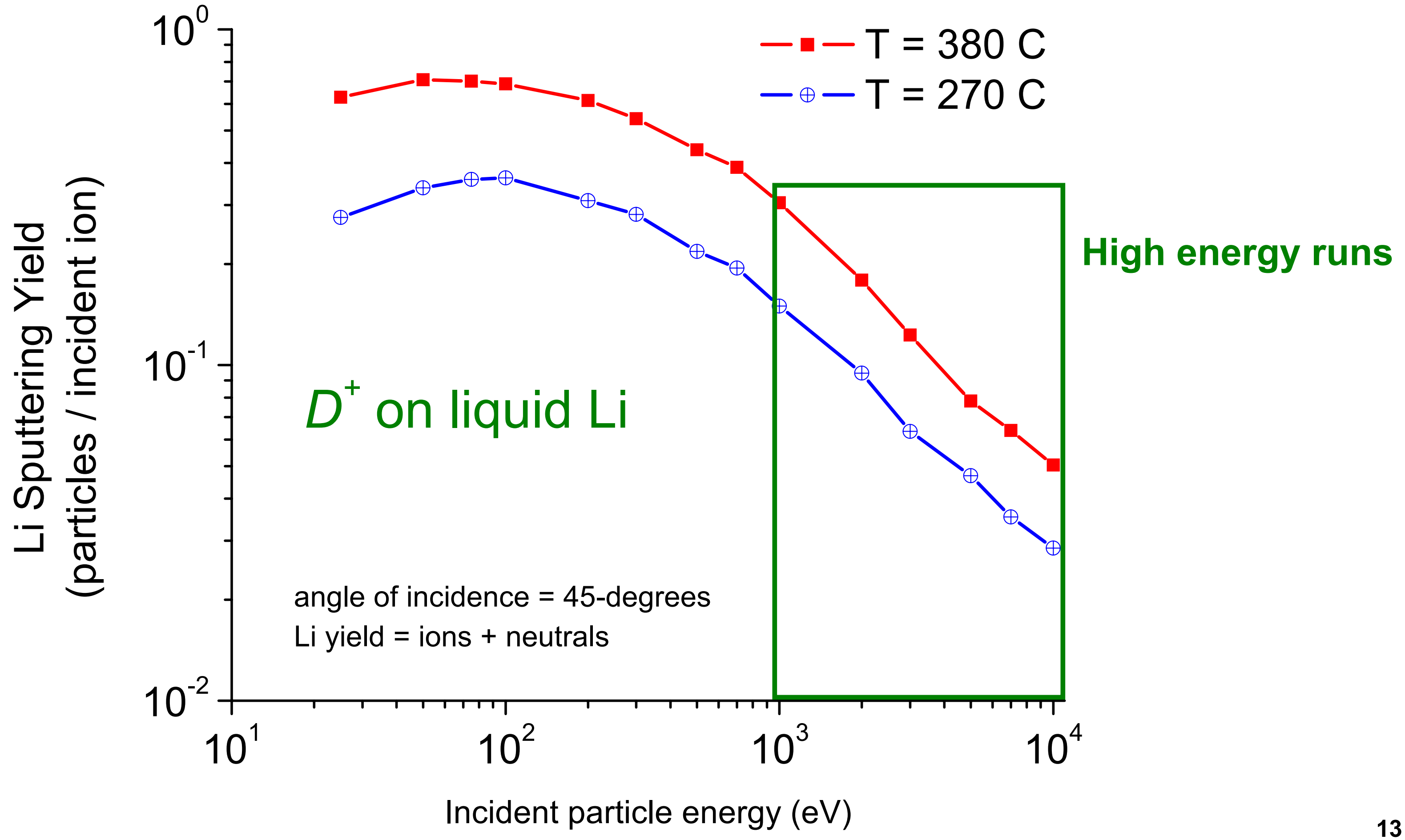
- **Empirical fits made to calibrated VFTRIM-3D runs**
- **Fits are completed for sputtering yields of lithium as a function of:**
  - Incident particle energy
  - Surface temperature
  - Incident angle
- **The fit is made to a temperature-dependent function (from P. Sigmund model)**
- **Empirical fits used in WBC/REDEP transport code**

Energy-dependent sputtering yields for liquid lithium (low-energy levels)

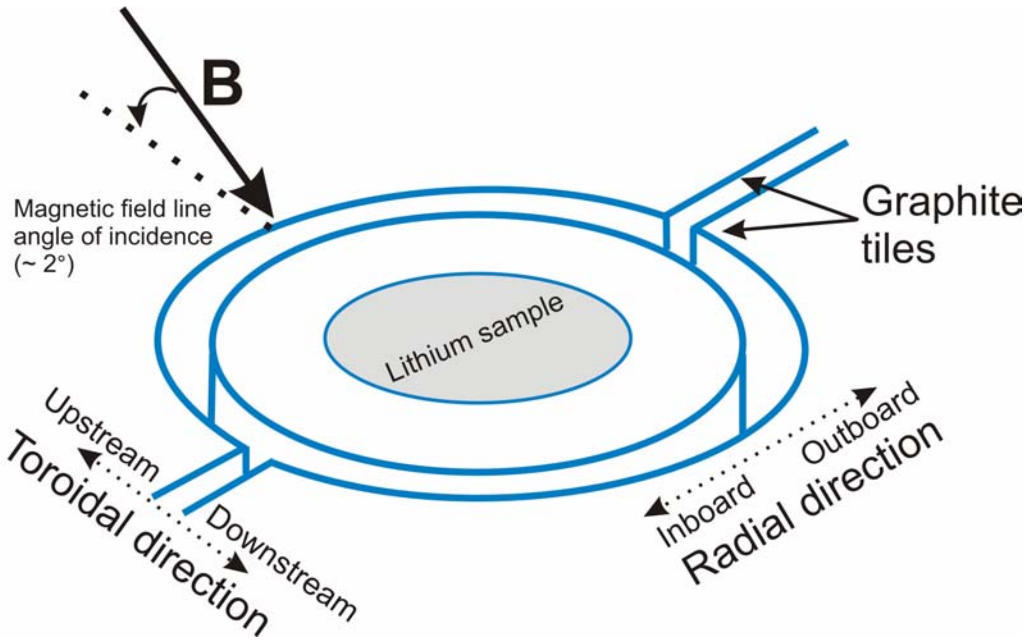


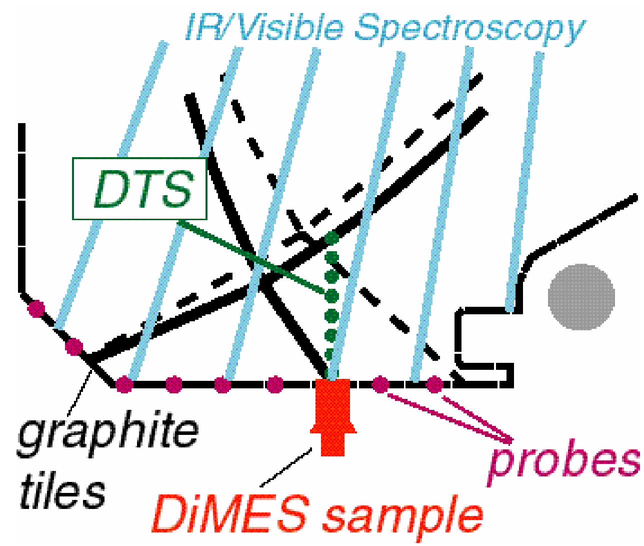
Sputtering yields for liquid lithium at higher incident energies

Plasma solution: “case 53”



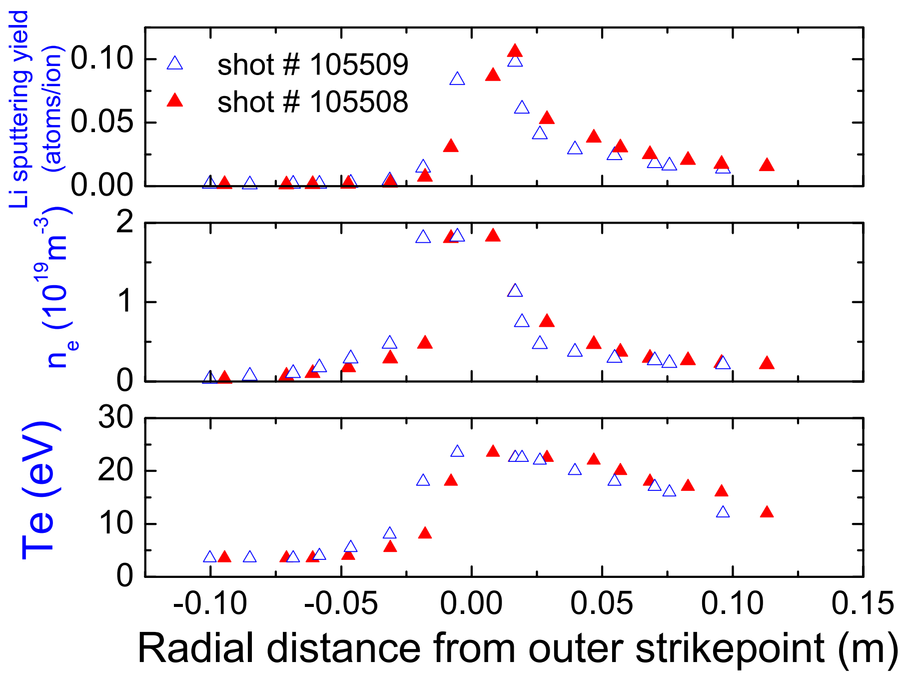
Li-DiMES experiments under quiescent plasma conditions

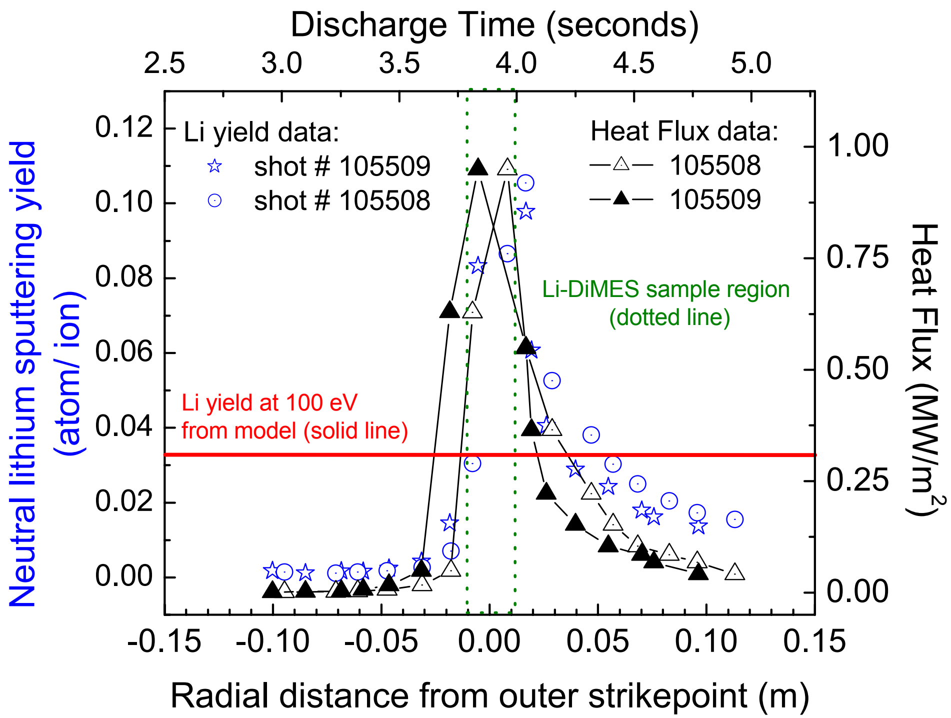




- DiMES with a 2.5 cm lithium spot as PFC in quiescent plasma discharges
- Plasma diagnostics and atomic lithium visible spectroscopy
- Diagnostics near outer strike point (OSP) with swept plasmas

Quiescent plasmas in Li-DiMES experiments

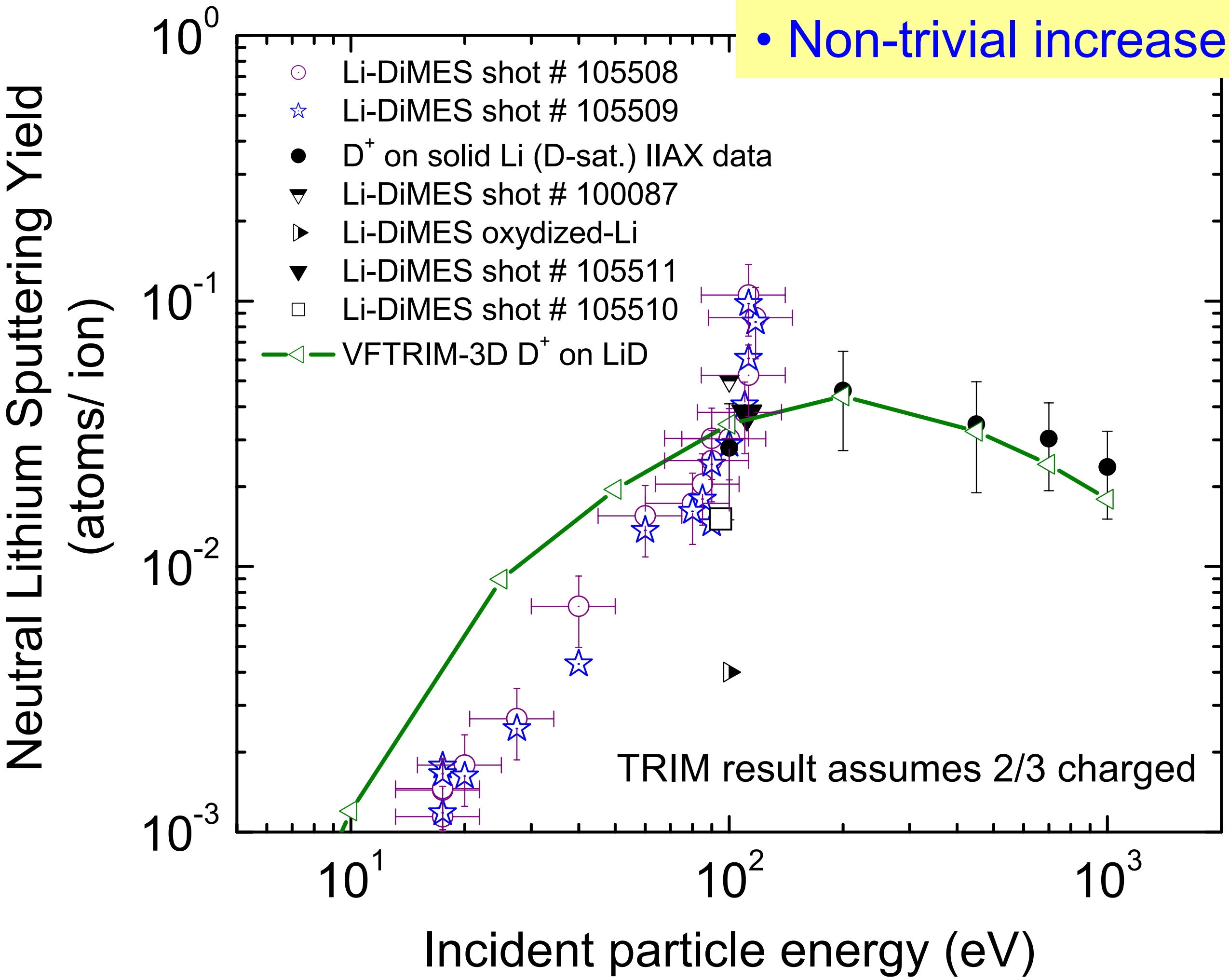




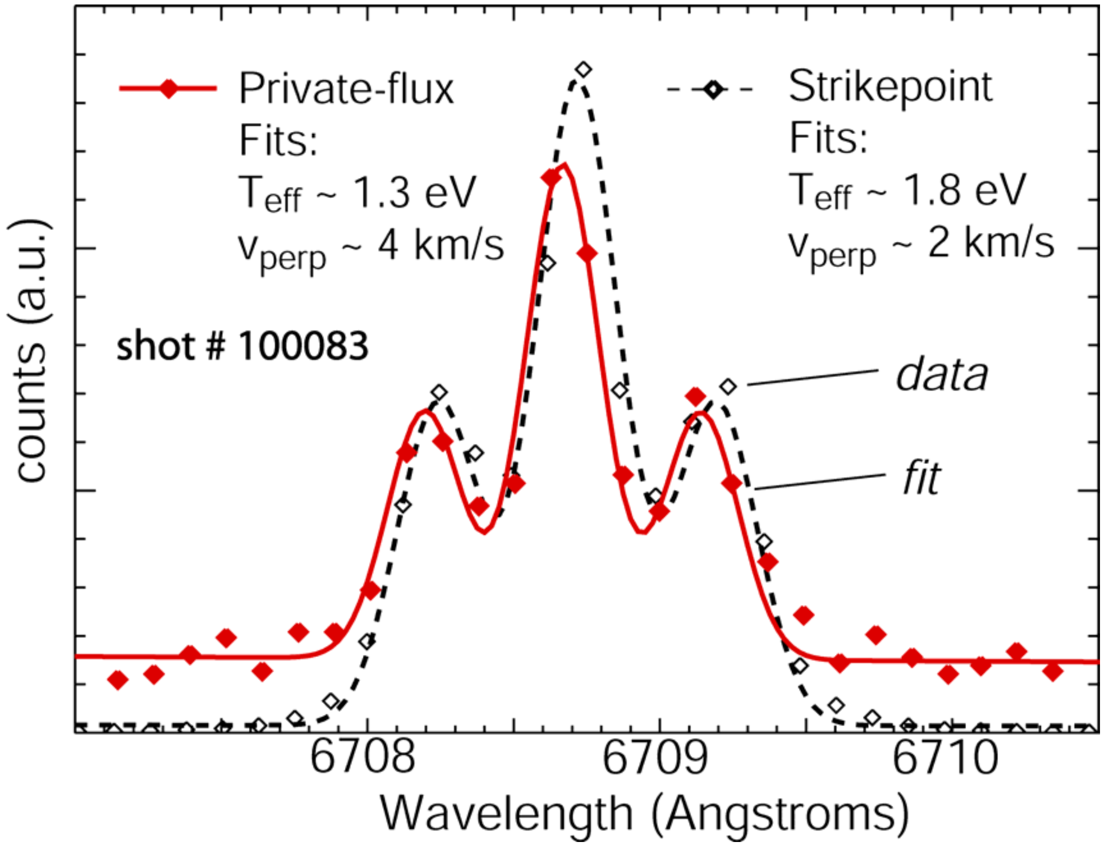
- **Electron temperatures ~ 5-25 eV**
- **Electron densities ~ 0.03 – 1.80 × 10^{19} m^{-3}**

Li-DiMES sputtering of D^+ on lithium

• Non-trivial increase in Li sputtering

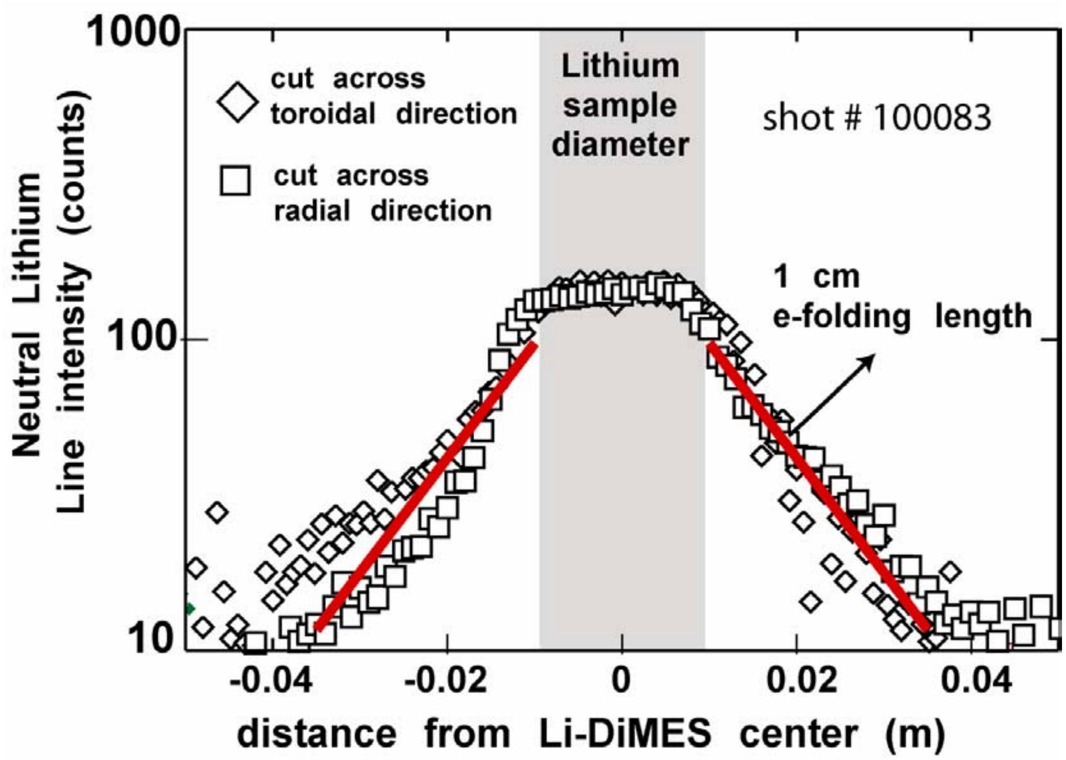


Li-DiMES able to measure erosion mechanisms in both PF and SP regions

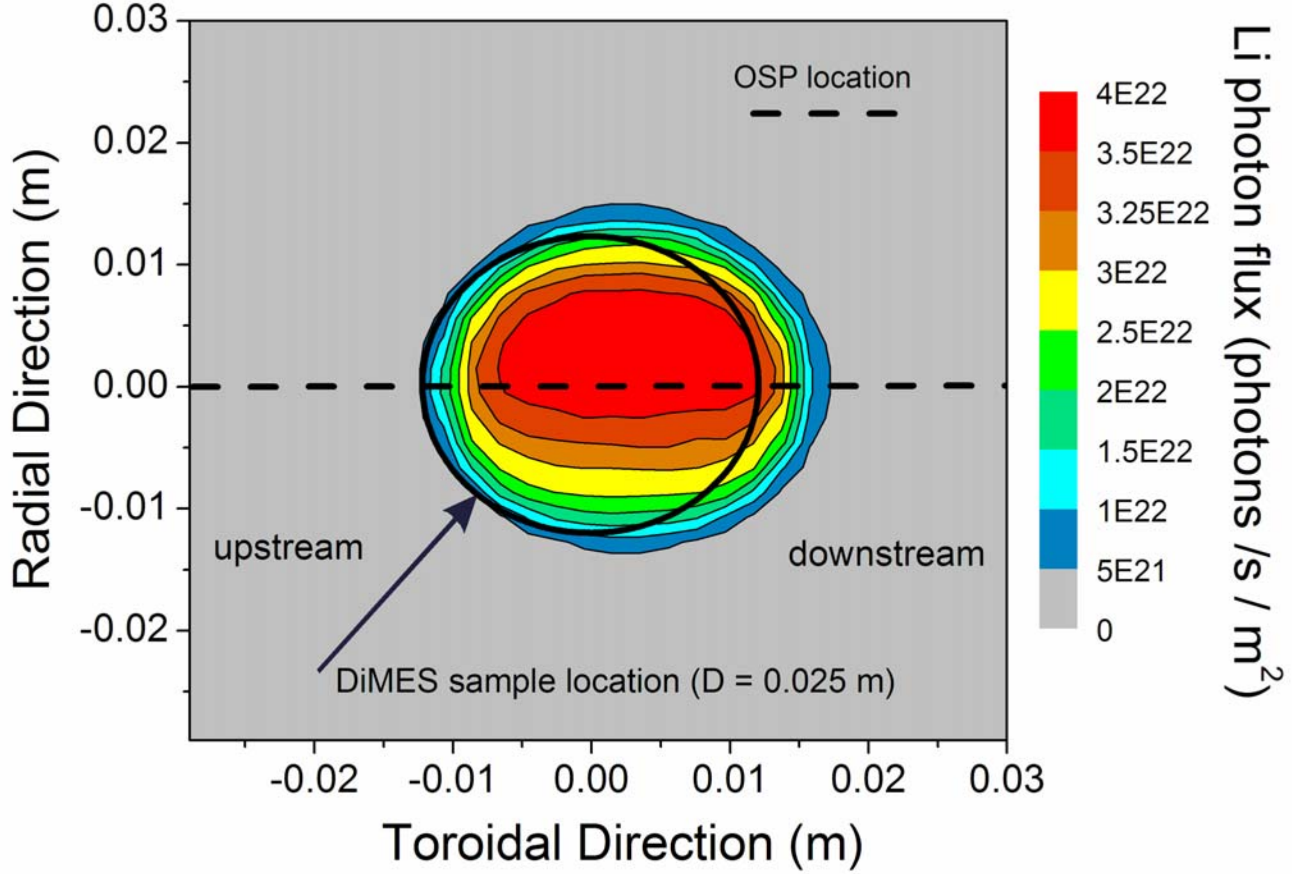


Neutral Li line intensity vs distance from Li-DiMES center

- Private flux bombardment in H-mode plasma
- Electron temperatures are low, ~ 1eV
- Electron densities ~ 10^{20} m^{-3}
- Ionization occurs a centimeter away and is confirmed with WBC/REDEP modeling data



Calculated Li I (671 nm) brightness with OSP on DiMES center



Li-DiMES code/data photon emission comparison, solid lithium

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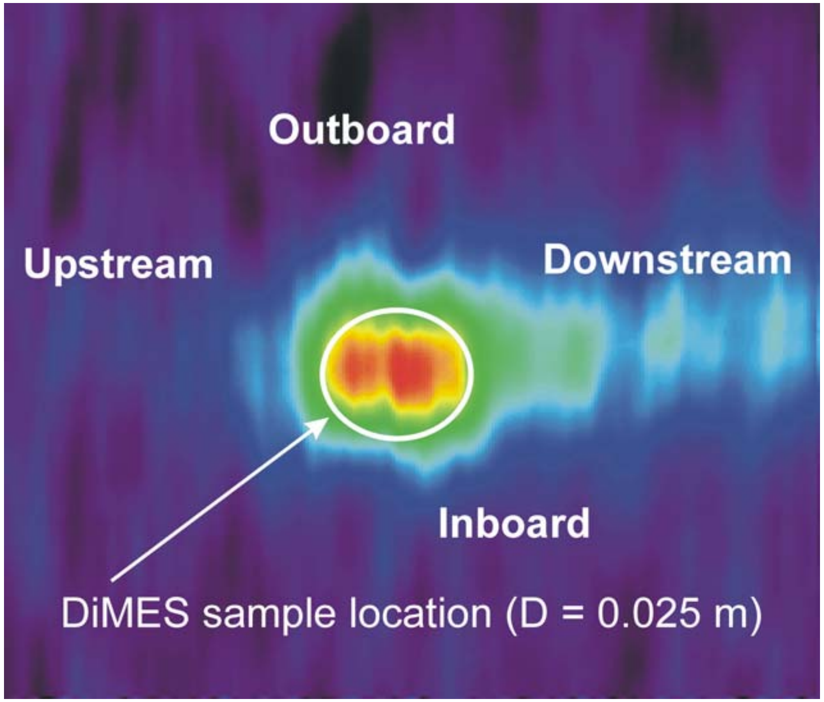

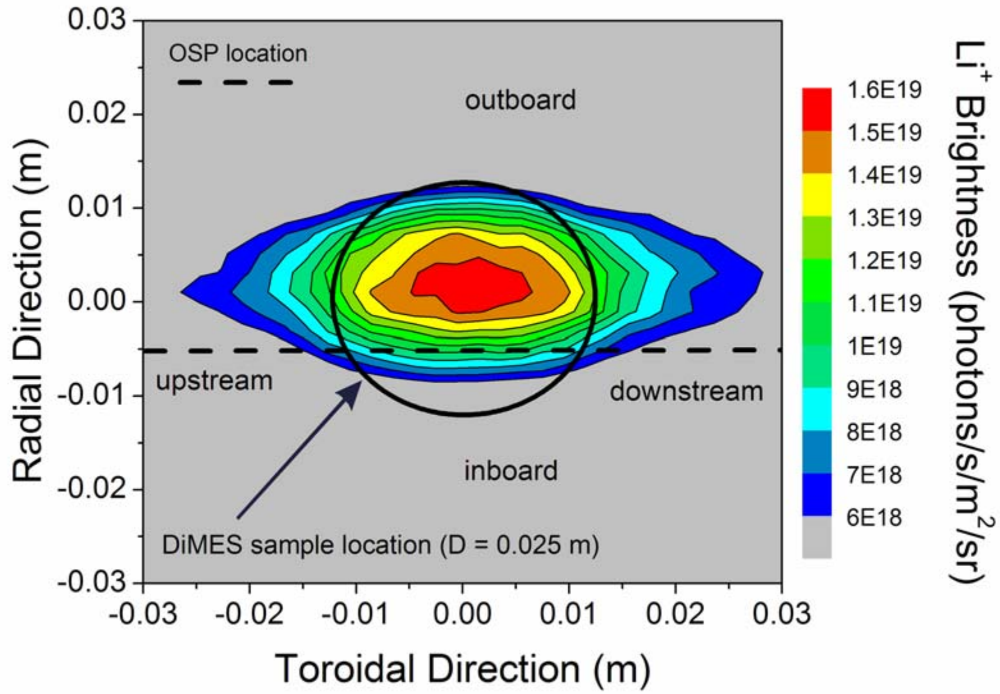

- Good agreement code/data

Summary and Conclusions

- Atomistic simulations helping elucidate erosion enhancement effects in liquid-metals and hot solids (e.g. Be)
- Further experiments/modeling needed:
  - **Testing effect of bubble formation on erosion enhancement in liquid metals**
  - **Charge dynamics of candidate LM PFCs**
  - **Low-energy reflection (need atomistic modeling with proper surface potentials)**
- NSTX cases modeled with calibrated surface models
- **Li-DiMES erosion results from quiescent plasmas**
  - Measured yield ~ 10% for T_e ~ 20 eV
  - Sputtered Li readily ionized near surface

Acknowledgements

- **PMI Group at the UIUC, D.N. Ruzic**
  - See: J.P. Allain, et al. JNM 313-316 (2003) 641 and M.D. Coventry, et al. JNM 313-316 (2003) 636
- **PISCES-B group**
  - See: R.P. Doerner, et al. JNM 313-316 (2003) 383
- **C. Wong and the DiMES team**
  - See: SOFE 2003 paper titled: "DiMES Contributions to PMI Understanding" C.P.C. Wong, et al. for more details