"Plasma Surface Interaction (PSI) Modeling of Liquid Lithium Divertors for the NSTX Tokamak"

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NSTX Lithium Systems

- Module A: static pre-shot deposited (~300 nm), pre-heated liquid lithium, on 1) carbon or 2) W-Cu or Mo-Cu substrate (Majeski et al.)
- Module B: in-shot injected flowing (10 m/s) lithium divertor (Ulrickson et al.)
- Present focus is on Module A analysis--most PSI issues for Module B are similar.

Critical Plasma Surface Interaction Issues

- D^+ pumping by the lithium.
- Edge/SOL plasma low-recycle plasma parameters.
- Power handling capability of Li on substrate.
- Erosion/redeposition--sputter net erosion, core plasma contamination, Li transport to other surfaces.
- ELM etc, response (see Hassanein et al.).

Module A System Analyzed

- ~3000 Å liquid lithium on ~30 cm wide radialy by $2\pi R$ toroidal divertor.
- Lithium on 1) carbon substrate or 2) copper substrate with thin W or Mo interlayer.
- Separatrix swept at 0, 5, 10 cm/s for 2 s

Analysis Method

- Plasma edge/sol--UEDGE fluid code, plasma heating power = 2, 3, 4 MW, with edge density bc's ⇒ **plasma solution**
- D^+ pumping--use plasma solution D^+ flux to surface +VFTRIM code + trapping and diffusion data/analysis⇒ **pumping capability**
- Surface temperature--use plasma solution heat load profile + sweep rate input to thermal code ⇒ **time-dependent temperature profile**
- Erosion/redeposition--REDEP/WBC kinetic code with updated sputter yield model + plasma solution + surface temperature input ⇒ **sputtered Li transport**
- Core plasma contamination: UEDGE + WBC

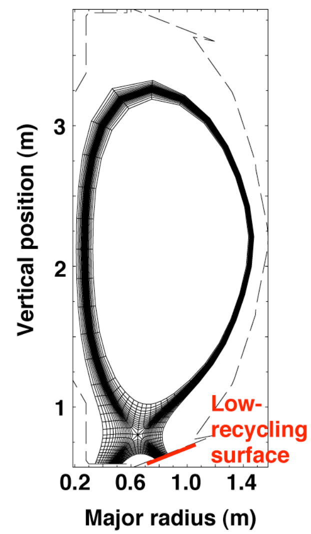
Not analyzed now

- Evaporation temperature limit — previous work [Brooks, Naujoks: Phys. Plasmas 7(2002)2565, J. Nuc. Mat. 290-293(2001)1123.] on sheath-superheat analysis shows ~ 500°C Li limit. Need analysis with specific NSTX magnetic field, and low-recycle plasma parameters.

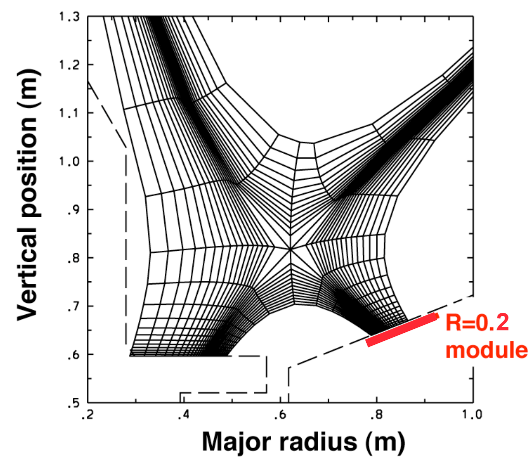
Lithium on outer NSTX divertor provides strong pumping and low-recycling divertor plasma

- **2D UEDGE fluid transport with kinetic corrections for deuterium plasma**
- **Base-case from high recycling (shot 109034, Porter)**
  - P_{core} = 2 MW
  - D = 0.5 m^2/s, χ = 1.5 m^2/s
  - R = 1.0
  - Wall gas albedo = 0.95
  - Carbon impurity
- **Outer plate recycling R = 0.2 yields hot, low density SOL**

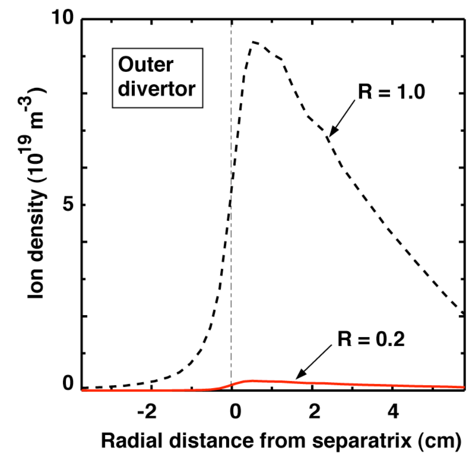
NSTX simulation region

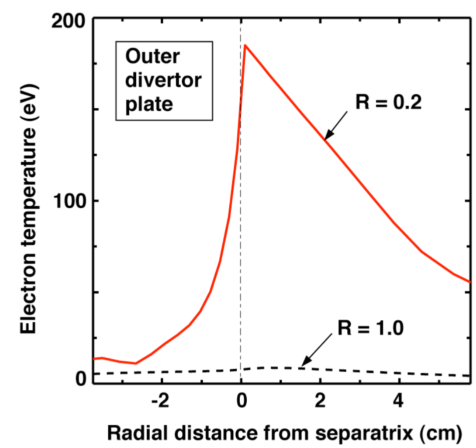


NSTX divertor region + Li module



Calculated N_i and T_e on outer divertor plate





NSTX MODULE-A Pumping Estimate

(follow up to Majeski et al. estimate)

- D^+ current to module, from UEDGE results, $I_D = 1.3 \times 10^{22}$ s^{-1} $\Rightarrow$ **2.6x10²²** D to module for 2 s pulse.

- Implanted D^+ distance (deepest) varies from about 1000-2000 Å , for 500-2000 eV D^+ @ 45 ° incidence [VFTRIM runs J.P. Allain (3/04)]

- Li diffusion distance, d >> per-shot-deposited Li depth, therefore assume trapping in entire depth. Therefore, order of 2500 Å depth of lithium available for trapping.

- Li trapping volume: V = 0.3 m x 5.4 m x 2500 Å = 4.1×10^{-7} m^3 $\Rightarrow$ **2.7×10^{22} Li atoms.**

Pumping continued

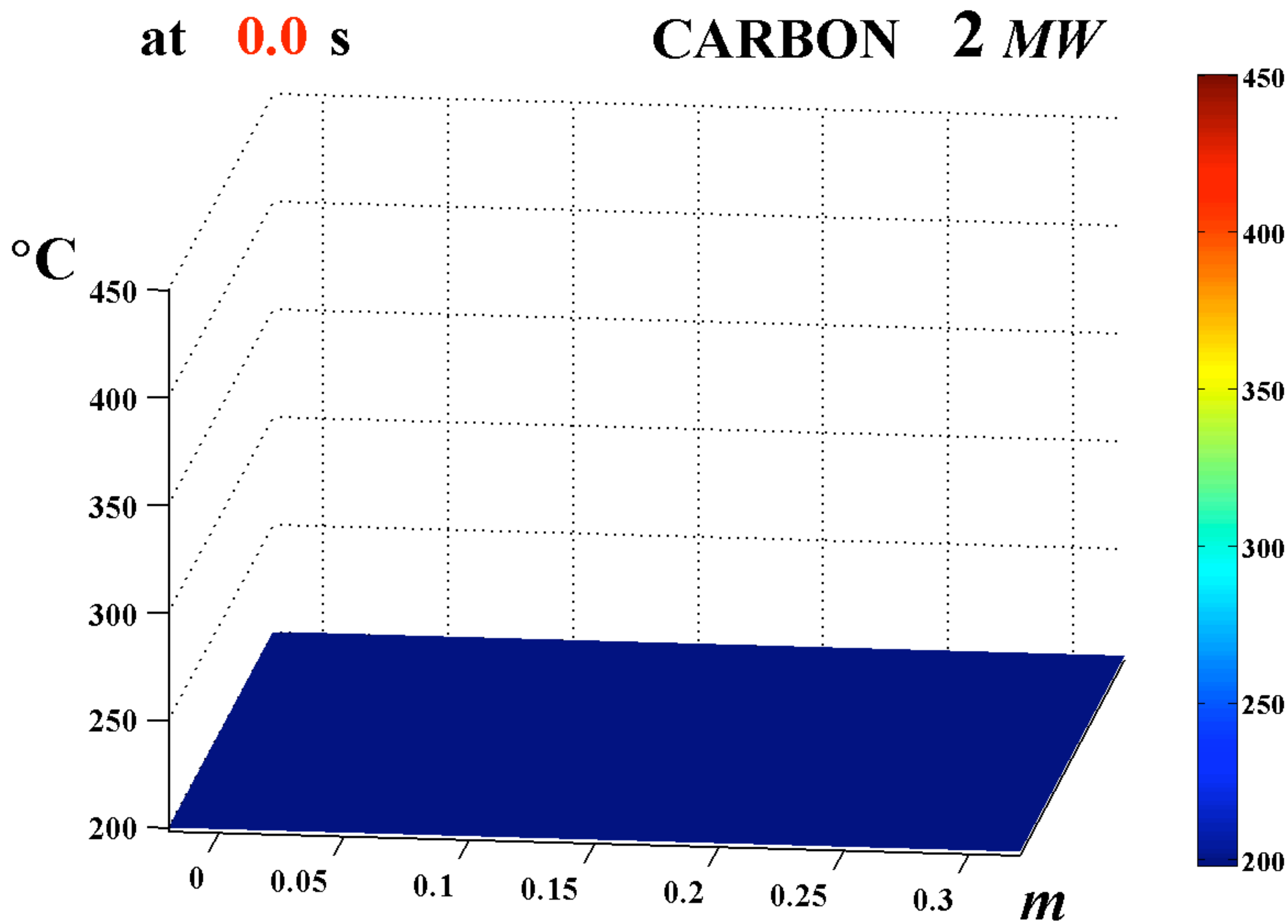
- **PISCES* and other data supports D/Li ~ 1 trap ratio. Therefore D trapping capacity ~ 2.7 x 10^{22} D/shot.**
- **Conclusion: One coating of lithium can enable full 2-s low-recycle shot.**
- **(Refueling issue-as pointed out by R. Majeski et al, the trapped D is more than the plasma content-must seriously refuel-work needed)**

*Deuterium retention in liquid lithium", M.J. Baldwin, R.P. Doerner, S.C. Luckhardt, R.W. Conn, Nuclear Fusion 42(2002)131.

Lithium surface temperature- Module A

- Simplified 1-D thermal code analysis.
- Heat flux from plasma solutions.
- Assumes heat conduction governed by substrate properties.
- Carbon and copper substrates analyzed.
- Different sweep rates analyzed.

Lithium surface temperature, carbon substrate, 10 cm/s sweep rate, 2 MW plasma heating power



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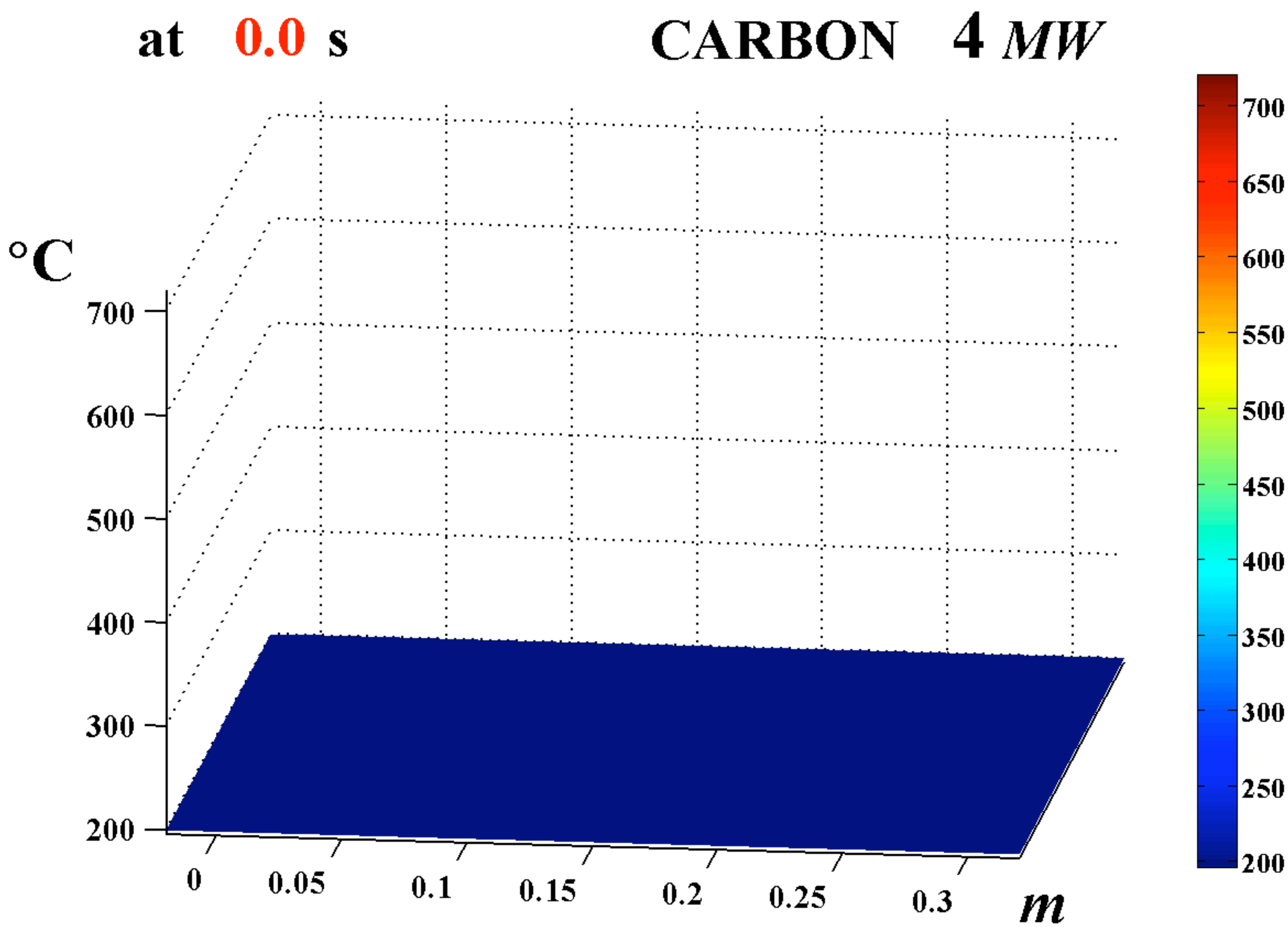
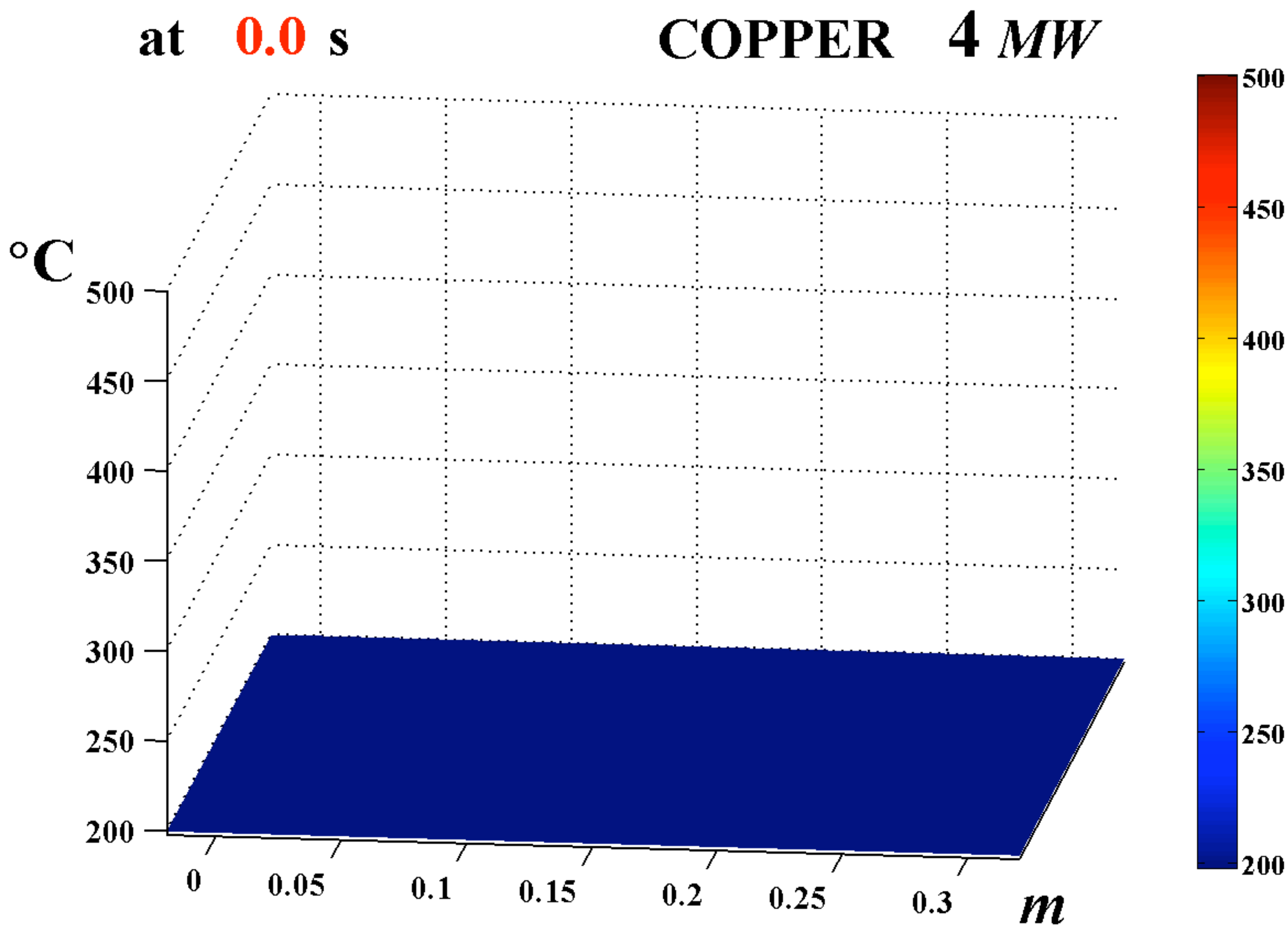
Lithium surface temperature, carbon substrate, 10 cm/s sweeping, 4 MW plasma heating power



Lithium surface temperature, copper substrate, 10 cm/s sweeping, 4 MW plasma heating power



NSTX Lithium Module A
Erosion/Redeposition Analysis

- *REDEP/WBC code simulation of 10 cm radial instantaneous x* ***2 s sweep @ 10 cm/s****, x 2πR toroidal static lithium module.*
- *Using 2-D plasma parameters from UEDGE cases, Input power = 2, 3, 4 MW; peak heat flux to divertor varies from ~ 8-20 MW/m^2*
- ***Temperature and energy dependent D^+, Li^+ lithium sputtering model (Allain).***
- Lithium surface temperature: Profiles from thermal analysis, for carbon, copper substrates. (only acceptable cases examined)
- *Li^+ sputtered transport model (Brooks) with MOLDYN computed (Allain, Alman) lithium reflection and charge state parameters.* *Net atom sputtering ~ Y/2, for total yield "Y".*

- *Li atoms sputtered self-consistently from entire module surface by D^+ sputtering and self-sputtering.*

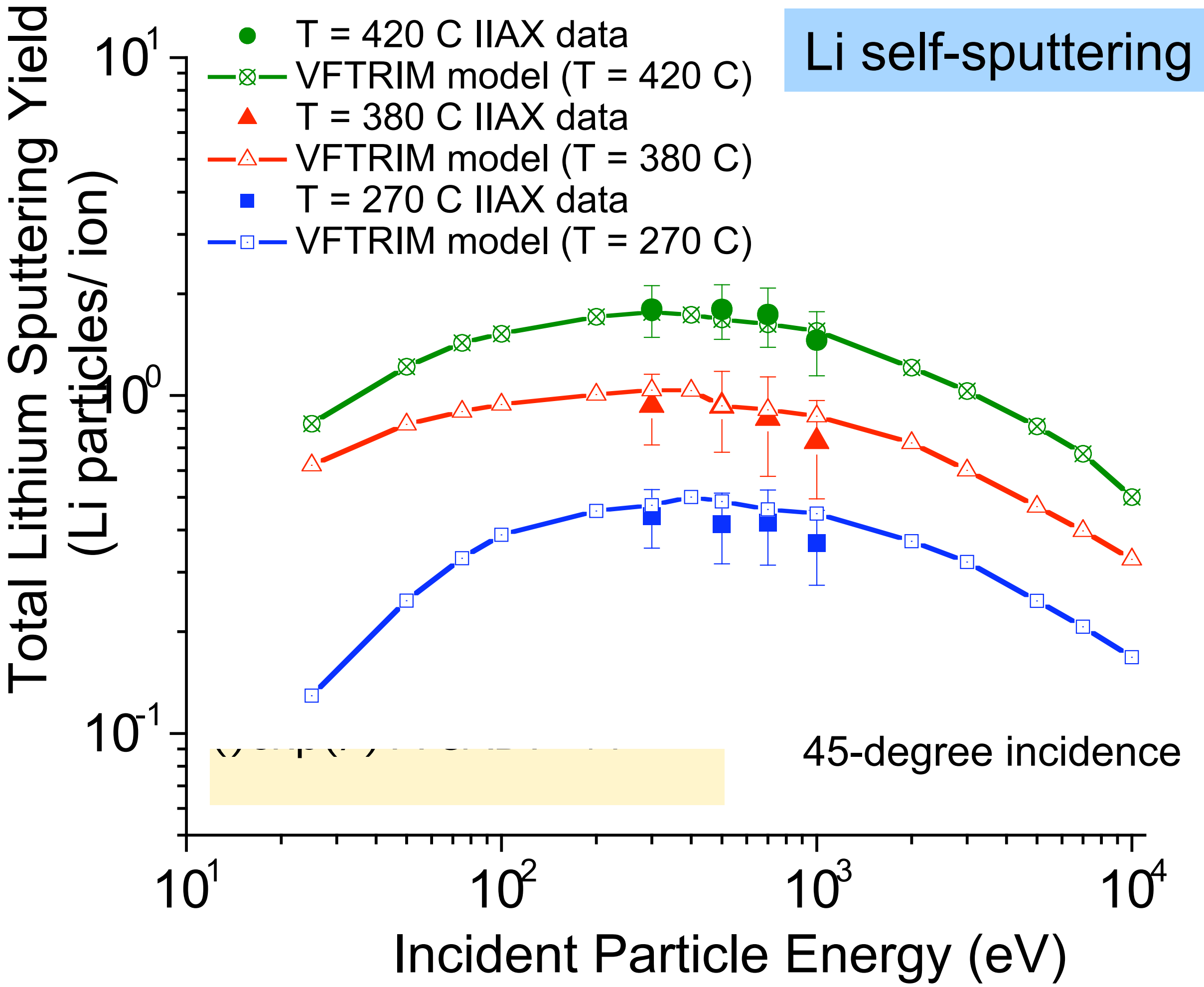
- *VFTRIM-3D-verified Thompson random collision cascade sputtered velocity distribution.*

- *ADAS rate coefficients (Evans, Whyte) for electron-impact ionization of Li-I, Li-II, Li-III particles.*

- *[100,000 particles launched per simulation]*

Energy-dependent sputtering yields for NSTX Li thin-film applications

- **Temp-dependent empirical fits made to data-calibrated VFTRIM-3D runs**
- **Fits are completed for lithium sputter yields as a function of incident energy, angle and temperature**
- **The fit is made to a temperature-dependent function (from P. Sigmund model)**
- **Empirical fits used in WBC/REDEP transport code**



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Erosion/redeposition-key results

- Sweeping is of major help—factor of 20 reduction in peak net erosion = good maintenance of lithium layer during shot.
- Results for 2, 3, 4 MW case plasmas are qualitatively similar.

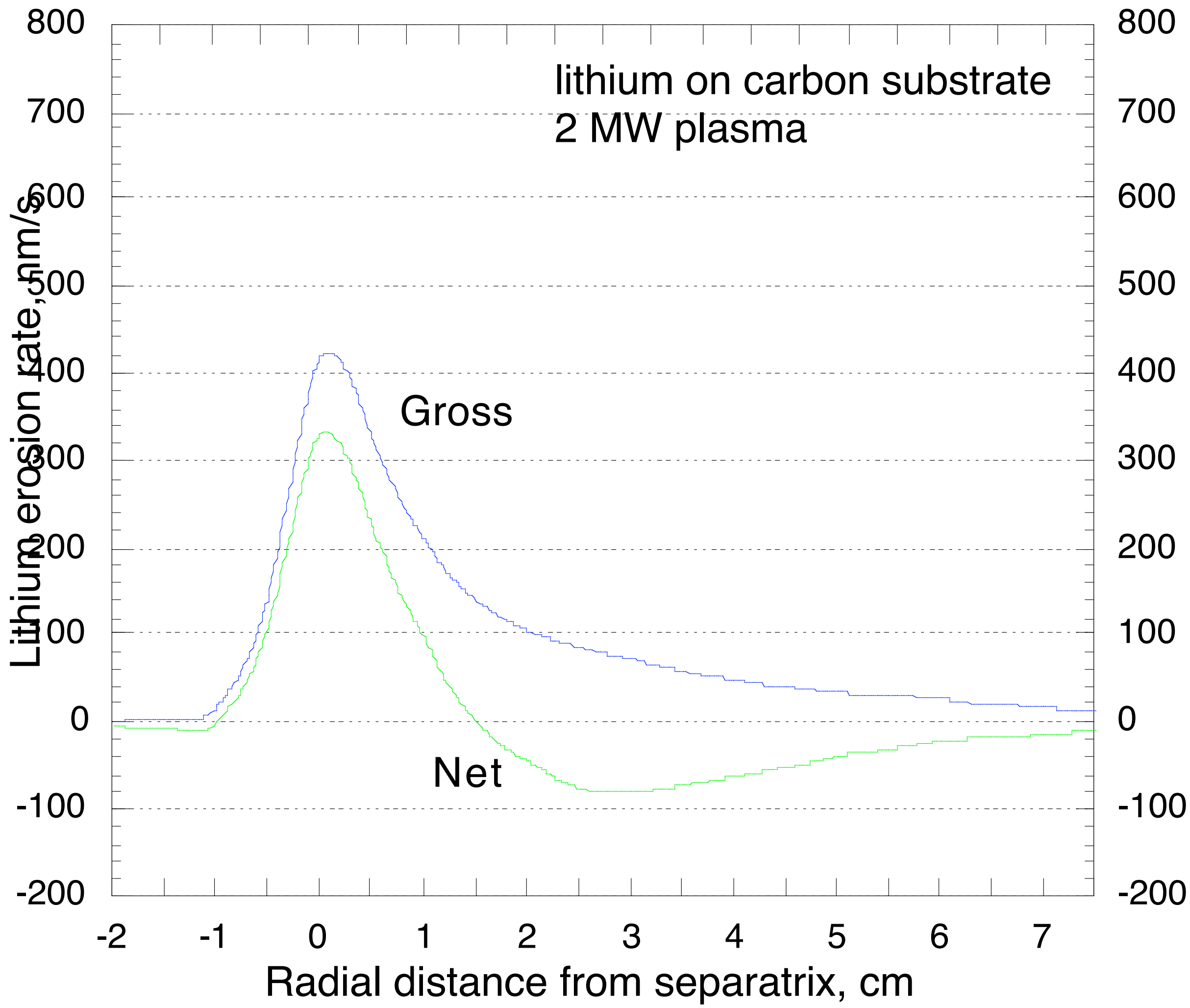

Figure 1 NSTX Module A lithium net sputtering erosion rate profile at 1000 ms. Carbon substrate, 2 MW plasma input power, 10 cm/s sweep rate.

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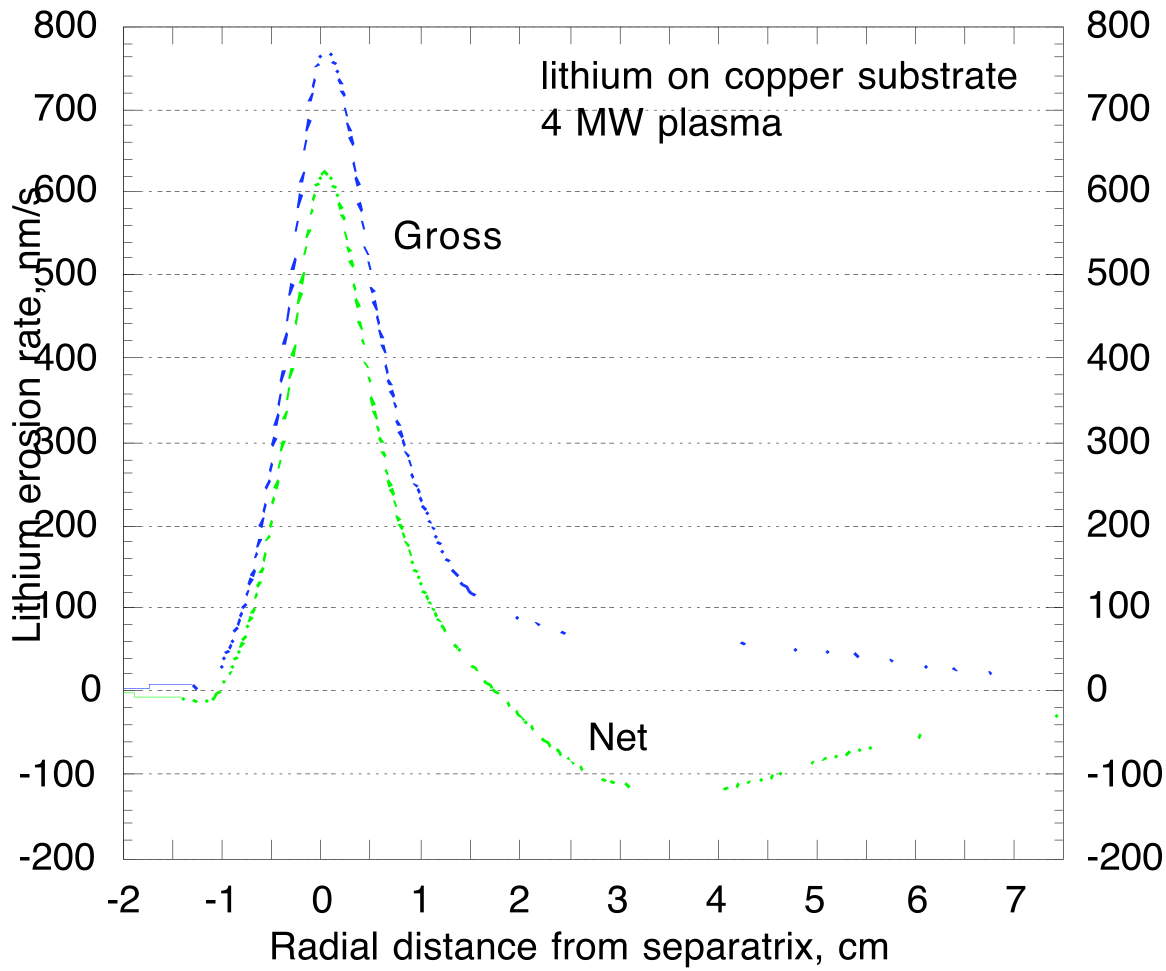


Figure 2 NSTX Module A lithium net sputtering erosion rate profile at 700 ms. Copper substrate, 4 MW plasma input power, 10 cm/s sweep rate.

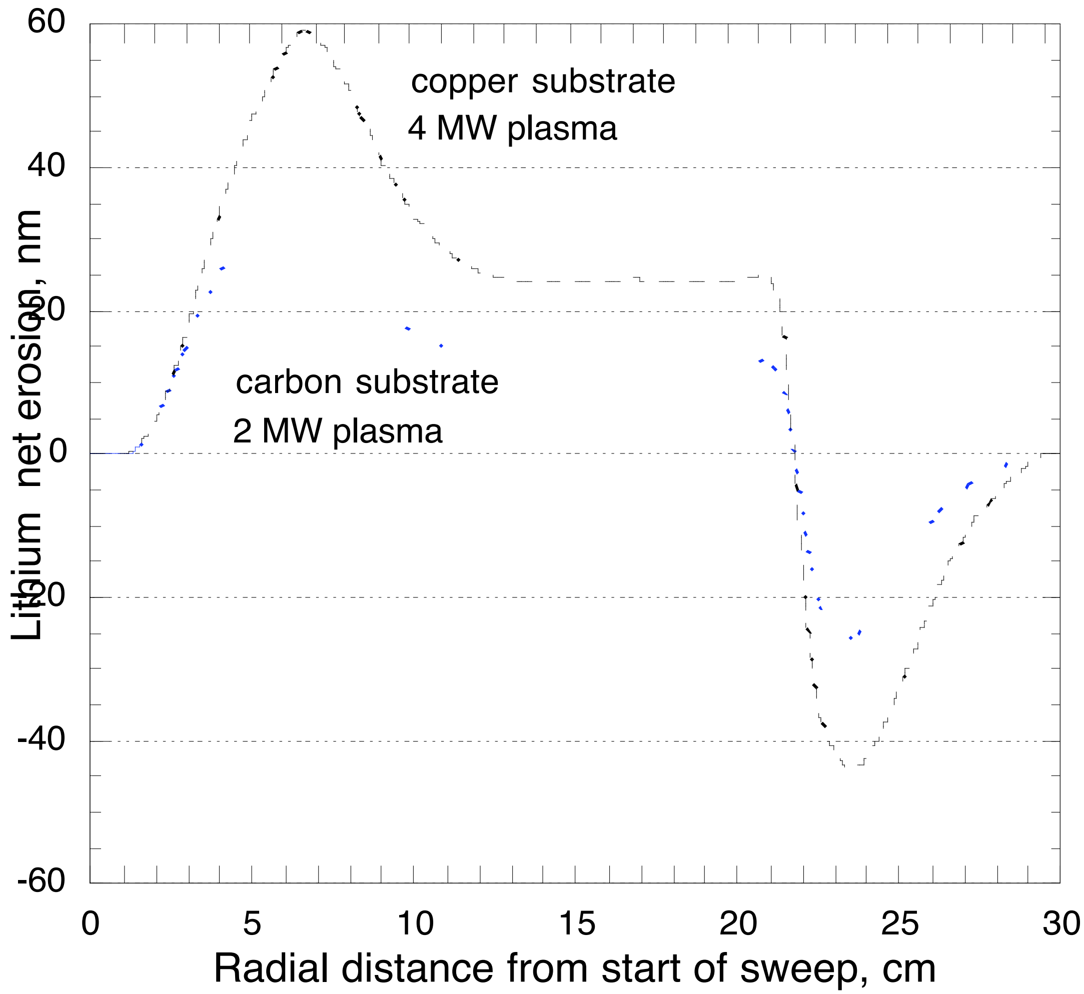


Figure 3 NSTX Module A lithium net sputter erosion at 2 s end-of-shot. Erosion computed from convolution of swept-plasma net sputter erosion rates for 0-2 s. (Separatrix swept from 2 cm to 22 cm.) (Gravity effect on liquid Li, if any, not included).

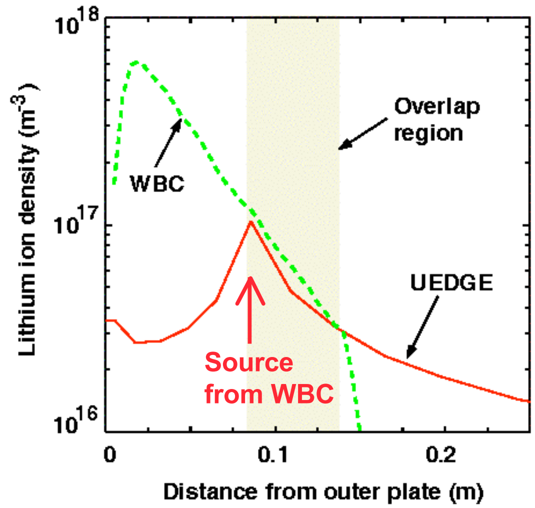
WBC provides UEDGE with lithium ion source 8 cm from outer plate; results in low Li core density

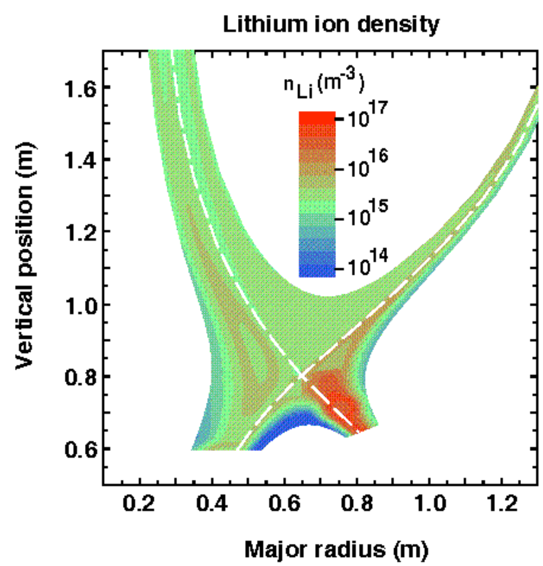
- WBC calculates the lithium ion density from sputtering and evaporation within 14 cm of plate

- UEDGE uses WBC Li source at 8 cm to evolve full SOL Li density

- Lithium is well entrained in divertor region from friction with hydrogen & downward E-field

- Midplane lithium density at core boundary is ~10^{-4} hydrogen density





Erosion/redeposition results continued

- Peak net erosion: ~ 30-60 nm @ 2s

- Sputter fraction lost to lower SOL outer boundary: ~ 15% . Not tracked here but transport to adjacent wall is likely.

- Bare tungsten strip analyzed: looks “OK”

Future PSI Work-Module A

- Evaporation/sheath-superheat analysis-to further define surface temp. limits for NSTX boundary conditions.
- Further WBC/UEDGE coupled analysis of Li transported to first wall.
- Incorporate data, as available, for Li on substrate properties.
- Other cases as needed (sweep rates, heating powers, etc.), 2-D thermal analysis.

Conclusions

- Integrated plasma surface interaction analysis performed for Module A.
- Results are favorable-*with assumption of working deposition process.*
- Li/C works for 2 MW heating. Li/(Mo/W)/Cu works for 2-4 MW, with up to 20 MW/m^2 heat load , w/sweeping.
- Module A should highly pump D.
- A 300 nm deposited Li surface is 80-90% retained under sputtering.
- Negligible core plasma contamination.
- *Low recycle regime is of major potential importance to NSTX physics mission.*
- Concerns include: Lithium transport to wall, fueling; evaporation analysis needed.