Overview: ALPS/APEX Plasma Edge & Plasma Material Interaction Modeling Group

Jeffrey N. Brooks

ALPS/APEX meeting, San Diego, April 2002
“Plasma-Surface-Interaction Analysis of NSTX Lithium Module and Related Issues”
J.N. Brooks, ANL

- **Integrated NSTX lithium erosion analysis**
  REDEP/WBC sputtering erosion analysis using:
  1. *UEDGE* (Ronglien et al.) low-recycle plasma parameters
  2. Lithium surface temperature (Ulrickson et al.)
  3. $T_s$-dependent sputter yields (Allain et al.)
  4. $\text{Li}^+$ transport model (Brooks, Allain et al.)

- **Sputtered $\text{Li}^+$ transport model**
  Issue and 1st-order model defined, detailed work in progress (with UIUC).

- **Sheath superheat analysis**
  BPHI-3D code analysis of NSTX lithium hot spot. Surface temperature limit analysis based on evaporation and superheat sheath theory.

- **DIII-D**
  Work continues on DiMES Li 99 solid-phase experiment analysis via WBC code, IIAX/VFTRIM sputter yields. Good match with data. Integrated SOL analysis underway via coupling to MCI. (with D. Whyte, T. Evans, D. Ruzic, et al.).
Integrated NSTX lithium erosion analysis

• Geometry: divertor module, ~ 8 cm poloidal by 40 cm toroidal.

• 2-D Plasma profiles: UEDGE Case sn_34; core power into the SOL = 6.0 MW, core-edge density = 4 x10^{19} m^{-3}. Peak heat load ~ 25 MW/m^2.

• Lithium surface temperature: SNL calculation for 10 m/s Li flow, UEDGE plasma heat loads: T_s varies from 220 to 471 °C.

• D^+, Li^+ sputter yields: UIUC data/model, Y=Y(energy, species, T_s) for 45° incidence.

• First-order charged sputtered particle transport model.

• WBC calculation of self-consistent lithium sputtering from module, lithium flux to SOL. Next step: coupling to UEDGE.
Sputtered Li$^+$ transport

- Most (~2/3) sputtered lithium is in the form of ions (IIAX, PISCES, previous data). These are generally ignored in erosion analysis.

- What happens to the sputtered lithium ions?

- “Conventional wisdom” is that these ions are “invisible” to the plasma—they return to the surface immediately due to the sheath electric field and the near-tangential magnetic field, and have no further effect.

- That is true to zeroth-order but due to high neutral self-sputtering, we are concerned with more detail. We need to consider transport of the sputtered charged lithium, and in particular, reflection and charge state of redeposited Li$^+$ ions.
Sputtered Li\(^+\) Transport Model

**Parameters:**
- \( R \) = Li\(^+\) reflection coefficient
- \( \varepsilon \) = charge fraction of reflected lithium
- \( Y_0 \) = Li\(^0\) sputtering coefficient

Then, Li\(^0\) sputtering with reflection:

\[
Y^{\text{total}} = Y_0 \times f(R, \varepsilon)
\]

NSTX: \( E \sim 10^7 \) V/m
\( \rho \sim 10^{-4} \) C/m\(^2\)
Study of low energy lithium self-bombardment reflection

• Sputtered lithium particles leave with a peak energy between 1-2 eV for incident particle energies ranging from 200-700 eV.
• Neutral sputtered particles are ionized very close to the lithium surface and return with nearly the same energy.
• Need to determine lithium self-particle reflection coefficient and an estimate of its charge state at these energies.
• BCA methods are limited at energies below 50-100 eV, therefore MD simulations are conducted.
Liquid lithium simulation setup

- Temperature control is achieved by using a simple velocity scaling technique at each time step\textsuperscript{1-3} to maintain the desired temperature at the edges of the surface.
- The resulting target surface is an amorphous liquid lithium surface 42.2 by 42.2 Å and 34.2 Å deep.

Reflected Li from liquid Li surface

- 45-degree incidence and 2 eV incident particle energy
- Self particle reflection coefficient for lithium atoms at 473 K is $0.39 \pm 0.037$
- The average energy of reflected lithium atoms is 0.354 eV with a standard deviation of 0.325 eV
- The charge state of reflected particles can range from 75-80% consistent with previous secondary ion sputtered fraction results and results in the literature\textsuperscript{1,2}

Lithium at 2 eV, 45 degrees on liquid lithium
Results of low energy lithium self-bombardment reflection from liquid lithium

- Self particle reflection coefficient for lithium atoms at 473 K is $0.39 \pm 0.037$.
- The average energy of reflected lithium atoms is 0.354 eV with a standard deviation of 0.325 eV.
- This case is for 45-degree incidence and 2 eV incident particle energy.
- The charge state of reflected particles can range from 75-80% consistent with previous secondary ion sputtered fraction results and results in the literature$^{1,2}$.

Nonorthogonal mesh with actual NSTX divertor surfaces

Proposed Lithium Module Location
NSTX “HIGH POWER”

![Graphs showing ion density, ion & electron temperatures, ion particle flux, and total heat flux as functions of radial distance.](image)
Figures 6 (a-d). Liquid lithium sputtering from Li bombardment at 45-degree incidence plotted versus target temperature with empirical fits for a variety of incident particle energies.

\[ Y(T) = C + A \exp\left(-\frac{B}{T}\right) \]
**NSTX Lithium Module**  
**Erosion/Redeposition Analysis**

**REDEP/WBC code simulation** of 8 cm poloidal x by 40 cm toroidal flowing lithium module.

*Using 2-D plasma parameters/profiles from UEDGE Case sn_34; Core power into the SOL = 6.0 MW, core-edge density = 4x10^{19} \ m^{-3}.*

*Temp-dependent lithium sputtering model (Allain).*

*Li^+ sputtered transport model with R=0.5, \( \varepsilon =2/3 \)*

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

*VFTRIM-3D/random-collision-cascade sputtered velocity distribution* (with cutoff energy determined by D^+ ion impingement energy and resulting maximum momentum transfer)

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

*[100,000 particles launched per simulation]*
NSTX Li module erosion; Key Results:

- Self-sputtering yield exceeds unity at and near strike point.

- Overall self-sputtering is finite (non-runaway).

- Overall lithium sputtering is high.

- Lithium current to SOL/near-surface boundary is high.

- Module area < 1/10 divertor area helps.
BPHI-3D Analysis: Lithium NSTX Module with 1 cm dia. circle hot-spot
Deuterium plasma, $T_e = 80$ ev, $T_i = 40$ ev, $T_s = 540$ °C, $B = 0.5$ T,
$N_e=1.0e19$ m$^{-3}$, $\theta = 13$ °, $G = 0.25$
MODELS INTEGRATION OF VARIOUS BEAM-TARGET INTERACTION PHYSICS IN HEIGHTS

Hassanein (ANL)
HEIGHTS Calculations of Lithium Response to ELMs
(ELM Energy =10% Q₀)

Hassanein (ANL)
HEIGHTS Analysis of Copper Structure Surface Temperature during Vertical Displacement Events (VDEs)

Copper Surface Temperature, K

Time, s

W

Be

Li

VDE

5 mm W or Be Coating or 20 mm Carbon Tiles on 5 mm Cu Substrate

60 MJ/m²

300 ms

Interface

W/ Be/ C Coatings or Tiles

Cu Substrate

Hassanein (ANL)
HEIGHTS Calculations of He Pumping Coefficient as a Function of Lithium Velocity

LITHIUM

$E = 10$ keV

$D_0 = 10^{-6}$

$D_0 = 10^{-5}$ cm$^2$/s

$D_0 = 10^{-4}$

Hassanein (ANL)
Lithium induced disruptions in DIII-D analysis and modeling

T. E. Evans, D. G. Whyte, C. P. C. Wong and W. P. West

- In DIII-D any attempt to place a solid lithium sample near the outer strike point disrupts the discharge.
- Data from two experiments suggest that the lithium sample melts and is partially injected into the core by a single MHD event which then triggers the disruption.
- The detailed analysis of a low power lithium disruption shot will be discussed.
- A conceptual model of the SOL current distribution during the initial liquid lithium phase has been developed
  - with this initial condition it may be possible to reproduce the injection event by numerical modeling the dynamics of the sample in the liquid phase
In a low power DIII-D L-mode plasma the core lithium emission looks like that of a single pellet.

The first peak in the core Li is when the injected droplet hits the separatrix, the second is the core ablation peak and the third is a locked mode.
CONCLUSIONS

- Integrated (plasma, $T_s$, $Y$) lithium sputtering erosion/redeposition analysis performed for proposed NSTX lithium module with high-power plasma case. Analysis shows high Li sputtering but probably non-runaway. Next step = low-power cases, WBC/UEDGE coupling to compute sputtered lithium current to core plasma.

- Sputtered lithium ion transport model developed. Molecular dynamic calculations show 2 eV Li$^+$ reflection coeff. $\sim 0.4$, high reflected charge state.

- Sheath superheat analysis initiated. Shows possibly higher surface temperature limit for runaway-onset for NSTX conditions.

- HEIGHTS code package analysis shows possibility of adequate helium pumping in flowing lithium.

- ELM lithium erosion analysis initiated with HEIGHTS. Very surprising and encouraging preliminary results regarding ELM erosion mitigation by vapor clouds etc.