“NSTX Lithium Module Erosion/Redeposition Analysis”

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- **Integrated NSTX lithium erosion analysis**

REDEP/WBC sputtering erosion analysis using:

1. UEDGE (Ronglien et al.) near-surface low-recycle plasma parameters: "**high-power case**" and "**low-power case**"
2. Lithium surface temperature (Ulrickson et al.) {*not self-consistent for high-power case}*
3. Surface temperature dependent sputter yields (Allain et al.)
4. Sputtered Li^+ transport model (Brooks, Allain et al.)

- **Sputtered Li^+ transport model**

Issue and 1st-order model defined, detailed work in progress (with UIUC).

- **WBC/UEDGE coupling**

Code (kinetic/fluid) coupling for complete SOL lithium transport calculations. WBC/UEDGE calibration & test study.

- **Runaway self-sputtering issue**

Self-consistent model (preliminary) developed for sputtered/redeposited lithium superheat, and effect on lithium surface temperature. **Runaway is a concern for high-power case**.

Integrated NSTX lithium erosion analysis

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

- 2-D Plasma profiles:

"High Power": UEDGE Case sn_34; core power into the SOL = 6.0 MW, core-edge density = 4 $\times 10^{19}$ m^{-3}. Peak heat load ~ 25 MW/m^2.

"Low Power: UEDGE Case sn_30; core power into the SOL = 1.5 MW, core-edge density = 1 $\times 10^{19}$ m^{-3}. Peak heat load ~ 5 MW/m^2.

- Lithium surface temperature: SNL calculation for 10 m/s Li flow, UEDGE plasma heat loads: T_s varies from 220 to: **470 (high-power)** , **270 °C (low power)**.

- D^+, Li^+ sputter yields: UIUC data/model, $Y=Y(\text{energy}, T_s)$ for 45° incidence.

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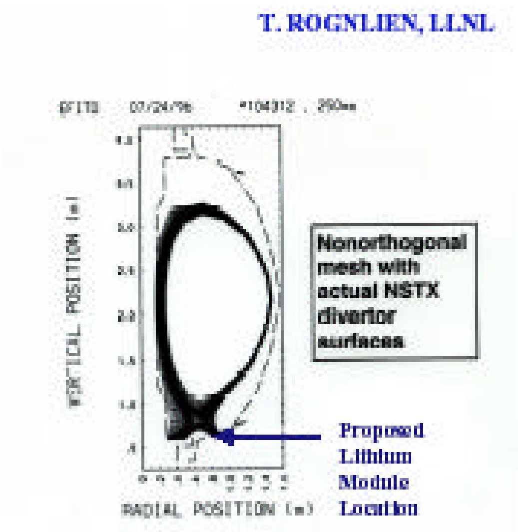
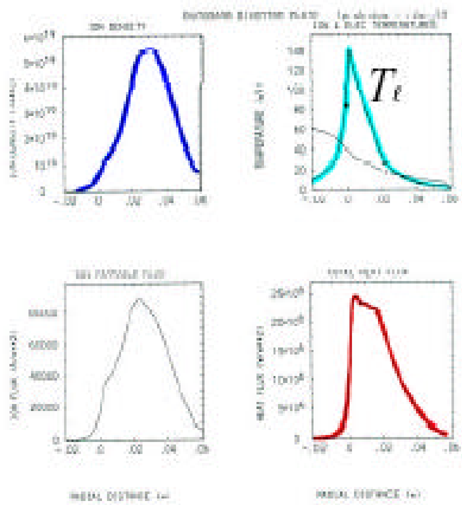
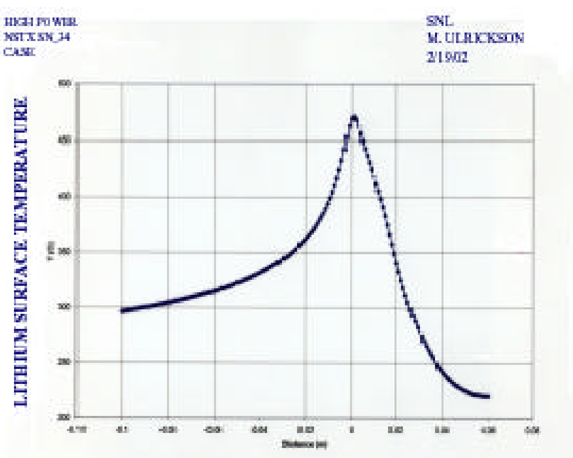
1/28/02

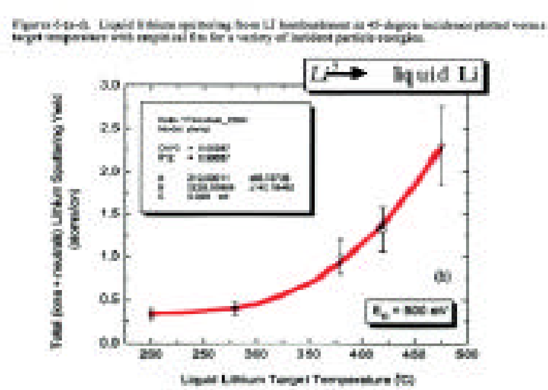


NSTX "HIGH POWER"





J.P. Allain
UIUC, 3/14/02



$$Y(T) = C + A \exp(-B/T)$$

WNSTX Lithium Module Erosion/Redeposition Analysis

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

2-D plasma parameters/profiles from UEDGE Cases sn_34, sn_30.

Temp-dependent lithium sputtering model (Allain)

Fixed surface temperature profiles** (Ulrickson et al.).***

Li^+ sputtered transport model with R=0.5, ε =2/3

Li atoms sputtered from 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:

High-Power Case:

- With the non self-consistent fixed-temperature condition, overall self-sputtering is high but finite (non-runaway). Lithium current to SOL/near-surface boundary is high. Module area ~ 1/16 divertor area helps in limiting overall plasma lithium contamination.

- With the self-consistent {Δ sputtering →Δ heat flux →Δ surface-temp. →Δ sputtering} feedback model (preliminary), runaway self-sputtering occurs.

Low-Power Case:

- Solution is well behaved, moderate lithium sputtering predicted.

WBC NSTX Lithium Analysis Summary

Parameter	**High Power Case*** **	**Low-Power Case**
Peak electron temp., heat flux	~140 eV, 25 MW/m^2	~110 eV, 5 MW/m^2
Charge state*	**1.002**	**1.002**
Angle of incidence* (from normal)	**17° (11°)**	**29° (12°)**
Energy*	**160 eV (96 eV)**	**94 eV (66 eV)**
D+ sputtering fraction	**0.45**	**0.89**
Self-sputtering fraction	**0.55**	**0.11**
Fraction of sputtered lithium escaping the near-surface region**	**0.05**	**0.13**
Sputtered lithium atom current	**3.4×10^{21} Li/s**	**1.4×10^{20} Li/s**
D^+ ion current to divertor	**1.0×10^{23} D^+/s**	**1.9×10^{22} D^+/s**
D^+ ion current to module	**7.5×10^{21} D^+/s**	**1.4×10^{21} D^+/s**
Peak Li/D ion density ratio above module	**~ 0.5**	**~0.25**

*average value (standard deviation) for redeposited ions
** (0-5 cm from plate)
*** with fixed surface temp. profile

Runaway Model

1. Lithium sputtering occurs due to D^+, Li^+ impingement, with fixed surface temperature profile, fixed plasma profiles.

2. **Lithium redeposited on module convects additional heat to divertor (sputter induced superheat).**

3. **Superheat increases the lithium surface temperature.**

4. **Increased surface temperature increases the sputter yields.**

5. **⇒Runaway self-sputtering, disruption likely.**

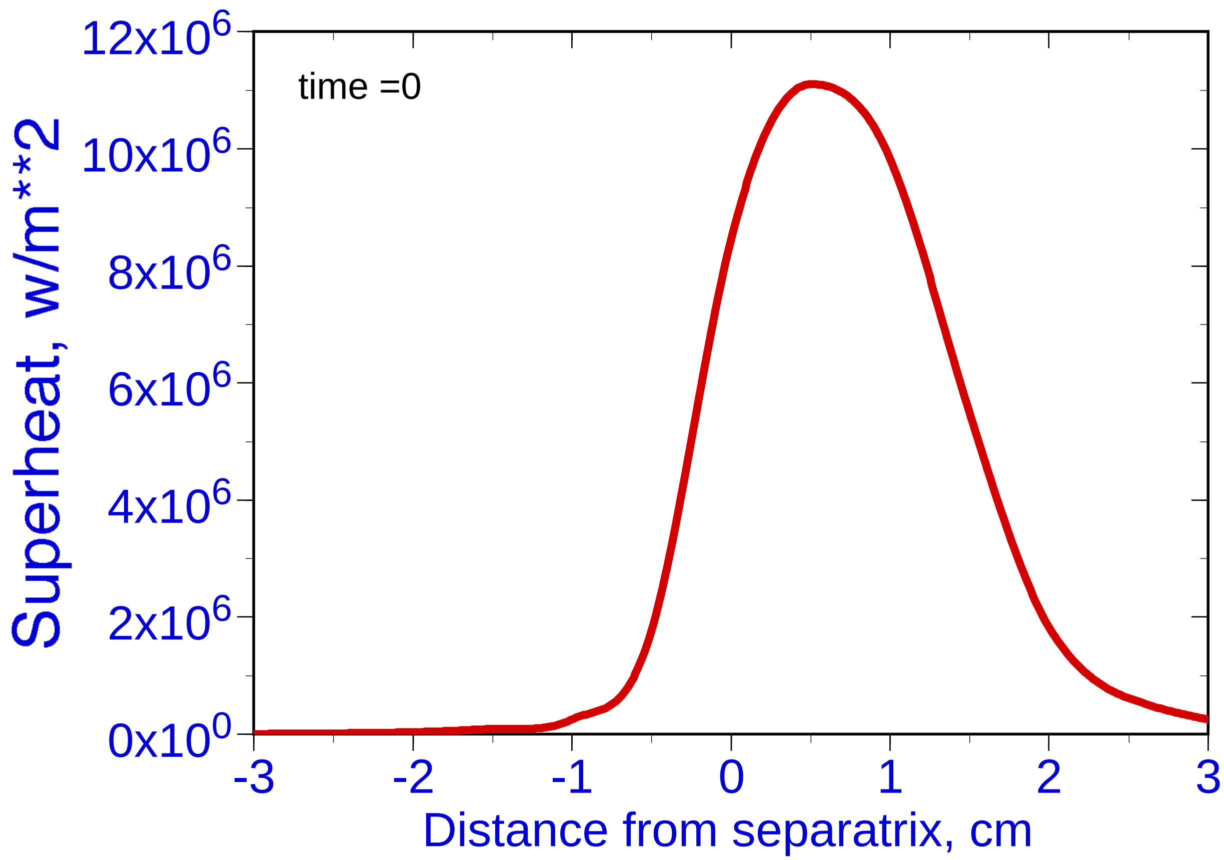
Runaway depends on lithium flow speed, plasma parameters, lithium sputtering dependence.

Does not occur with solid materials.

Could be self-limited with full-area divertor module due to plasma heat flow limitation, but more likely with limited-area module.

Runaway sets necessary condition for maximum surface temperature.

NSTX Lithium Module High-Power Case:
Sputter/redeposition Superheat-WBC analysis



Runaway- rough scaling:

lithium response— change in surface temperature, for heat flux Q :

$$\Delta T \approx 1.07x10^{-4} Q\sqrt{t}$$

**for ~ 2 cm superheat width @ 10 m/s flow speed:
exposure time t = .002 s**

**at t = 0 (start of runaway),
for superheat Q_s = 10 MW/m^2:
ΔT_s ~ 50 °C
T = T_0 + ΔT_s = 520 °C (new surface temperature)**

**at "new" temperature:
sputtering increases by factor of ~ 3
Q_s =36 MW/m^2
T = 692 °C**

→ runaway

Future Work

- Ongoing model improvements/coupling:

  new MOLDYN molecular dynamics code (UIUC) Li^+ results $\rightarrow$ WBC.

  High surface temperature sputtered velocity distribution (PISCES, IIAX data/models) $\rightarrow$ WBC.

- **More refined runaway model and estimates of acceptable peak lithium temperature for NSTX module. (ANL/SNL/UIUC)**

- **Ongoing WBC/UEDGE coupled analysis-to determine self-consistent lithium content in core and SOL plasma. (ANL/LLNL)**

CONCLUSIONS

- Integrated lithium erosion/redeposition analysis performed for proposed NSTX lithium module with low and high-power plasma cases. **Integration = fluid plasma + kinetic plasma + thermal response + sputter yields. Low power case well-behaved**. High power case OK for fixed surface temperature profile, problem for non-fixed.

- **Liquid metal sputter runaway phenomenon identified—preliminary model developed.**

- **High (but non-runaway) near-surface plasma lithium concentration (~ 50%) does not lead to high core plasma contamination.**

- **Key next step = Significant model improvements from molecular dynamics analysis, sputter data, etc. Key output = Tolerable NSTX plasma input power with lithium module, lithium flow requirements.**