Effect of Lithium Evaporation on the Edge Plasma in NSTX, and plans for NSTX-U


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Plasma characteristics and stability improved with increasing lithium evaporation in strongly shaped NSTX discharges

• Lithium evaporated before each discharge
  – Deposition amount scanned, as also in weakly shaped discharges
    (no liquid lithium divertor results in this talk)

• Global characteristics changed
  – Recycling: $D_\alpha$ declined in all measured views
  – Energy confinement ($\tau_E$, H-factor) improved
  – When discharges were ELM-free, radiated power increased with time (several techniques developed to deal with this problem)

• Edge $n_e$, $T_e$, pressure profiles changed
  – Reduction in edge $n_e$ gradient changed edge $P'$, improving MHD stability and eliminated ELMs in weakly shaped discharges
Outline

- Effect of lithium on individual discharges
- Trends vs. pre-discharge lithium dose
- Effect on edge profiles
- SOLPS edge transport analysis
New analysis from highly shaped plasma dataset as envisioned in NSTX-U, and for future STs

High $\delta$ (0.6)
High $\kappa$ (2.2)
High squareness
$I_p=1$ MA, $q_{95}=8.2$

Low $\delta$ (0.46)
Low $\kappa$ (1.8)
Low squareness
$I_p=0.8$ MA, $q_{95}=7.6$
Center of LITER deposition very near *(far from)* outer strike point in high *(low)* triangularity discharges.
Performance of strongly shaped discharges improved more with increasing lithium (similar to weakly shaped discharges)

- $I_p$ duration not quite optimized with higher Li
- Reduced $P_{NBI}$
- Reduced $dN/dt$
- Comparable stored energy
- H-factor increased by 50%
- Increasing $P_{rad}$ wo/ELMs
- Reduced recycling, long ELM-free phases

F. Scotti et al., *Nucl. Fusion* 53 (2013) 083001
Lower divertor \(D_\alpha\) decreased rapidly with increasing Li deposition in highly shaped discharges

- 5x drop in \(D_\alpha\) drop because of transition from high recycling to low recycling
  - Partial detachment in highly shaped no-Li discharges?
- Possible geometric effect: Li deposition closer to outer strike point and/or high flux expansion facilitates transition from high to low recycling at lower Li deposition in highly shaped discharges
$D_\alpha$ and neutral pressure decreased, and H97L increased with increasing pre-discharge lithium evaporation in all data.

- High shaping
- Low shaping
Edge profiles change markedly with increasing lithium in strongly shaped discharges (as in weakly shaped ones).

\[\text{n}_e \times 10^{20} \text{ m}^{-3}\]

\[T_e \text{ [keV]}\]

\[T_i \text{ [keV]}\]

\[P_{e+i} \text{ [kPa]}\]
Higher NBI power in strongly shaped discharges leads to high edge temperature and pressure.
Goal of SOLPS interpretive analysis is to assess recycling coefficient and radial transport changes with lithium

- Generate grid based on discharge equilibrium
- Prescribe power and particle fluxes through inner boundary from data
- Vary free parameters to match measured midplane and divertor profiles
  - Separatrix location adjusted to match peak $q_{\text{div}}^{\text{peak}}$
  - Plate recycling coefficient and radiation varied to match peak $D_\alpha$
  - Extra power-balance iteration allows complex $D(\psi)$, $\chi(\psi)$
  - No separation between $D$ and $v_{\text{pinch}}$, so diffusivities are ‘effective’ values, i.e. to get flux right

- Result: recycling coefficient drops from 0.99 to ~0.9
- Result: transport increases in last 3% of $\psi_N$, but decreases inside of that region
Reference no-lithium discharge has low heat flux & high $D_\alpha$: modeling indicates partially detached state.
Shallow edge $n_e$ gradient, deeper temperature gradients, and higher heat flux/lower $D_\alpha$ reproduced in modeling.

* Uncertainty in peak heat flux due to lithium use, no dual-band adapter.
Particle transport reduced with increasing lithium
Energy transport reduced a few cm inside of separatrix

- Increasing lithium in direction of yellow arrow
Trend of improving discharge performance with increasing lithium observed in highly shaped plasmas

• Recycling and neutral pressure decreased with increasing Li
• Energy confinement increased and edge stability improved with increasing Li
  – Divertor peak heat flux also increased substantially
• Recycling coefficient dropped to ~ 0.9 from 0.99 (SOLPS)
  – Li deposition close to strike point facilitates high -> low recycling?
• Transport increased in last 3\% of $\psi_N$, but decreased inside of that region (SOLPS)
• Change in edge profiles likely the key to ELM elimination, as in weakly shaped discharges
  – ELITE edge stability calculations commencing
  – Micro-stability assessment in progress
Lithium delivery tools being developed for NSTX-U

- Downward facing evaporators ~ Jan. 2016 (first lithium in NSTX-U: controlled scan as reported here)
- Upward facing evaporators ~ Fall 2016
- Impurity granule injector (ELM pacing, including, carbon, lithium, etc – see Lunsford poster) ~ Dec. 2015
- Lithium dropper ~ needs re-installation of guide tube (Fall 2016+)
- Pre-loaded lithium targets in divertor tiles ~ Fall 2017

- **Looking forward to conducting these types of experiments in NSTX-U!**
## Comparison of lithium results from NSTX, DIII-D, and EAST

<table>
<thead>
<tr>
<th></th>
<th>NSTX</th>
<th>DIII-D*</th>
<th>EAST**</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Delivery method</strong></td>
<td>Inter-shot evaporation, (Dropper)</td>
<td>Dropper</td>
<td>Dropper, (Morning evap., FLiLi Limiter)</td>
</tr>
<tr>
<td><strong>Pedestal Width</strong></td>
<td>Increased</td>
<td>Increased</td>
<td>?</td>
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<td>?</td>
</tr>
<tr>
<td><strong>H-factor</strong></td>
<td>Increased</td>
<td>Increased</td>
<td>Unchanged</td>
</tr>
<tr>
<td><strong>Edge fluctuations</strong></td>
<td>Decreased</td>
<td>Increased</td>
<td>Increased</td>
</tr>
<tr>
<td><strong>Radiated power</strong></td>
<td>Ramp during ELM-free phase</td>
<td>Steady in ELM-free phase</td>
<td>Steady in ELM-free phase</td>
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<tr>
<td><strong>Effect on ELMs</strong></td>
<td>Eliminated</td>
<td>Delayed</td>
<td>Eliminated</td>
</tr>
<tr>
<td><strong>Recycling</strong></td>
<td>Reduced</td>
<td>Unchanged</td>
<td>Reduced</td>
</tr>
</tbody>
</table>

ELMs disappeared gradually with increasing lithium (also observed in weakly shaped discharges)
ELM-free H-mode induced by lithium wall conditioning in weakly shaped discharges

- Pre-Li, with-Li (260 mg), with-Li (700 mg)
- Lower NBI to avoid $\beta$ limit
- Lower $n_e$
- Similar stored energy
- H-factor increased by 40%
- Higher $P_{rad}/P_{heat}$
- Reduced recycling, ELM-free with higher Li

D. Mansfield, JNM 2009; R. Maingi, PRL 2009
Lithium improved performance of strongly shaped discharges, similar to weakly shaped ones

- Duration extended
- Same $P_{\text{NBI}}$
- Reduced $\frac{dN}{dt}$
- Higher stored energy
- Higher confinement
- Increasing $P_{\text{rad}}$
- Reduced recycling, long ELM-free phases
Lithium reduced recycling and improved confinement of both strongly and weakly shaped discharges

Strong shaping

Weak shaping

No lithium

550 mg

710 mg
Similar effects on discharges observed with weak and strong shaping

- Duration extended
- Same and lower $P_{\text{NBI}}$
- Reduced $dN/dt$
- Higher stored energy
- Higher confinement
- Increasing $P_{\text{rad}}$
- Reduced recycling, long ELM-free phases
ELMs eliminated gradually during original low $\delta$ experiment
Power and particle exhaust a key challenge for future devices

- Liquid metals are being studied at PPPL as an alternative to solid PFCs for future devices

- NSTX used lithium wall coatings (evaporative and liquid) to test the efficacy of lithium in particle and power exhaust
  - Lithium enables reduced recycling from PFCs
  - Lithium will be important research line in NSTX-Upgrade, which is scheduled to commence operation in 2015
Flow chart of how lithium results in ELM elimination similar for highly and weakly shaped discharges

\[ \psi_N \text{ from 0.95-1 (recycling region)} \]

- Li coatings reduce recycling and core fueling (SOLPS)
- \( n_e \) and \( \nabla n_e \) reduced
- \( \nabla T_e \) fixed
- \( \chi_e \) increased
- ETG (GS2)
- \( n_e, P_e \) gradient reduced
- \( P_i \) gradient unchanged
- \( J_{bs}, J_{li} \) reduced - stabilizing (ELITE)

\[ \psi_N \text{ from 0.8-0.94} \]

- \( D_{eff} \) reduced, most in ELM-free (SOLPS)
- \( n_e \) and \( \nabla n_e \)
- \( T_e \) and \( \nabla T_e \) increased
- \( \chi_e \) reduced strongly – \( \mu T \) stable (GS2)
- Edge \( P_e \) follows \( n_e \) and \( T_e \); peak \( P' \) shifts farther from separatrix
- \( J_{bs}, J_{li} \) increased but far from separatrix; improves stability to kink/peeling modes (ELITE)