Edge transport and turbulence reduction, and formation of ultra-wide pedestals with lithium coated PFCs in NSTX

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Outline

• Introduction: ELM elimination and pedestal profile changes with lithium coatings

• SOLPS is used for interpretive modeling of the edge plasma

• Lithium coatings lead to widening of edge transport barrier
  – Two regions: stiff $T_e$ near separatrix, reduced transport at top of pedestal
  – Measurements show reduced fluctuations with lithium

• Discussion of candidate edge transport mechanisms
Type I ELMs eliminated, energy confinement improved with lithium wall coatings

- Without Li, With Li
- ELM-free, reduced divertor recycling
- Lower NBI to avoid $\beta$ limit
- Similar stored energy
- H-factor 40%↑

H. Kugel, PoP 2008
R. Kaita, IAEA 2008
M. Bell, PPCF 2009
$T_e$, $T_i$ increased and edge $n_e$ decreased with lithium coatings

No lithium

With lithium

separatrix
Peak pressure gradient moves inwards, $p'$ and $j$ reduced outside $\psi_N \sim 0.95$

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**Pre-Li**

- Stable
- Kink/Peeling Unstable
- $0.1$
- $0.05$

**Post-Li**

- Kink/Peeling Unstable
- $0.1$
- $0.05$

R Maingi, PRL 2009
Pre- and post-lithium discharges are modeled using SOLPS

- SOLPS (B2-EIRENE: 2D fluid plasma + MC neutrals) used to model NSTX experimental data
  - Neutrals contributions
  - Recycling changes due to lithium
  - $f$/Canik APS10 invited (PoP 11)

Parameters adjusted to fit data

<table>
<thead>
<tr>
<th>Parameters used to constrain code</th>
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<tbody>
<tr>
<td>Radial transport coefficients $D_\perp, \chi_e, \chi_i$</td>
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<tr>
<td>Divertor recycling coefficient</td>
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<td>Separatrix position/ $T_e^{sep}$</td>
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J. Canik, PoP 2011 submitted
Procedure for fitting midplane $n_e$, $T_e$, $T_i$ profiles

- Start with initial guess for $D_\perp$, $\chi_e$, $\chi_i$
- Run simulation for $\sim 10\%$ of confinement time
- Take radial fluxes along 1-D slice at midplane from code
  - $\Gamma_{\text{SOLPS}}, q_{e\text{ SOLPS}}, q_{i\text{ SOLPS}}$
- Update transport coefficients using SOLPS fluxes and experimental profiles
  - E.g., $D^{\text{new}} = -\Gamma_{\text{SOLPS}}/\text{grad}(n_e^{\text{EXP}})$
  - Here we use fits to profiles used in stability calculations (Maingi PRL ’09)
- Repeat until $n_e/T_e/T_i^{\text{SOLPS}} \sim n_e/T_e/T_i^{\text{EXP}}$

J. Canik, PoP 2011 submitted
Peak $D_\alpha$ brightness is matched to experiment to constrain PFC recycling coefficient: lithium reduces $R$ from $\sim 0.98$ to $\sim 0.9$

- For each discharge modeled, PFC recycling coefficient $R$ is scanned
  - Fits to midplane data are redone at each $R$ to maintain match to experiment
- $D_\alpha$ emissivity from code is integrated along lines of sight of camera, compared to measured values
  - Best fit indicates reduction of recycling from $R \sim 0.98$ to $R \sim 0.9$ when lithium coatings are applied
Midplane and divertor profiles from modeling compare well to experiment for the pre-lithium case

- $P=3.7$ MW
- $R=0.98$

- Good match to midplane profiles

- Carbon included: sputtering from PFCs, inward convection to match measured $n_C^{6+}$

- Heat flux and $D_\alpha$, radial decay sharper than experiment
Combining reduced recycling and transport changes gives match to measurements with lithium

- P=1.9 MW
- R=0.90

- Transport coefficients adjusted to recover fit to upstream data

- Good match to both peak and profile for heat flux and D_α (except PFR)

*Uncertainty exists in IR measurements, due to emissivity change with lithium films
Transport barrier widens with lithium coatings, broadening pedestal

- Pre-lithium case shows typical H-mode structure
  - Barrier region in $D$, $\chi_e$ just inside separatrix
- Pedestal is much wider with lithium
  - $D_\perp$, $\chi_e$ similar outside of $\psi_N \approx 0.95$
  - Low $D_\perp$, $\chi_e$ persist to inner boundary of simulation ($\psi_N \approx 0.8$)
- Changes to profiles with lithium are due to reduced fluxes combined with wide transport barrier
Particle and heat sources are reduced with lithium

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Transport barrier widens with lithium coatings, broadening pedestal

- Two regions considered
  - Top of pedestal
    - Large transport reduction
  - Bottom of pedestal
    - Transport similar with lithium
Outer region: $T_e$ gradient nearly constant outside of $\Psi_N \sim 0.95$

• Key to ELM suppression: reduction of current for $\Psi_N > .95$
  – Density is reduced with lithium, but $T_e$ unchanged
  – Pressure gradient is reduced $\rightarrow$ less bootstrap current

• Edge $\nabla T_e \sim$ constant, critical gradient?
  – Intermediate stages shown have less lithium, same $P_{NBI}$ as pre-lithium case

![Graph showing $T_e$ vs $\Psi_N$](image)

![Graph showing $\chi_e$ vs $\Psi_N$](image)
Inner region: as lithium coatings thicken, density barrier widens, pedestal-top $\chi_e$ reduced

- Several shots analyzed with increasing lithium thickness
- ELM$y$ to reduced frequency to ELM-free

- Barrier in particle transport widens with lithium thickness
- $\chi_e$ inside $\Psi_N \sim 0.95$ gradually reduced
Edge reflectometry near pedestal top shows reduced density fluctuations with lithium

- Reduced transport in inner region -> higher pedestal top pressure
- Reflectometer shows reduced fluctuation level
  - Pre-lithium: strong amplitude and phase fluctuation
  - Post-lithium: little amplitude fluctuation
  - 3D simulations using Kirchoff integral indicate turbulence level reduced from ~10% to ~1% with lithium
High-k scattering diagnostic shows little change in fluctuation amplitude at $k\rho_s > 10$

- Pre-to-post lithium transition repeated, similar profile changes observed
- Fluctuations similar for $k\rho_s > 10$, some reduction at lower $k$ for the with-lithium case
With power reduced so $T_e$ profile matches pre-lithium case, fluctuation amplitudes show broad reduction

- Power reduced to 2 MW
- $T_e$ profile similar to pre-lithium
- Fluctuation amplitude reduced across measured $k_\perp \rho_s$
BES also shows reduced turbulence levels in post-lithium discharges

*Courtesy D.R. Smith, UW*
ETG is unstable in steep gradient edge

- Investigating ETG stability with GYRO [1]
  - $\chi_e \sim 2-5 \left( \rho_e^2 v_{te}/L_{Te} \right)$, within range of nonlinear expectations
  - Electrons satisfy gyrokinetic ordering $\rho_e/L_{Te} < 1/400$

- ETG unstable in steep gradient region ($\psi_N > 0.92$)
  - Threshold likely set by density gradient
  - $\eta_{e,\text{crit}} \sim 1-1.25$ calculated in AUG edge [2], compared to core criteria $\eta_{e,\text{crit}} \sim 0.8$ [3]

- ETG stable at top of pedestal ($\psi_N = 0.88$)
  - Smaller density gradient, threshold likely sensitive to $Z_{\text{eff}} T_e/T_i$ and $s/q$

- Calculating thresholds and transport are work-in-progress

Measured pedestal modifications are consistent with paleoclassical transport

- Pedestal structure model based partly on paleoclassical transport proposed
  - J.D. Callen, UW-CPTC 10-9
  - Depends on resistivity profile -> $Z_{\text{eff}}$ changes important

- Model recovers $\chi_e$ magnitude, shape, rise near separatrix, as well as modest increase with lithium outside $\psi_N \sim 0.95$

- Density profile shape changes with lithium also captured by model
Edge transport is reduced, transport barrier widened with lithium coatings

- Measured pedestal profile changes with lithium are reproduced in 2-D edge modeling

- Matching midplane profiles requires change to transport coefficients in addition to recycling
  - Transport barrier widens with lithium, giving wider pedestal
  - $T_e$ gradient relatively unchanged outside $\psi_N \sim 0.95$

- Fluctuation measurements show reduced edge turbulence in inner pedestal region

- Future research will focus on possible transport mechanisms
  - ETG and paleoclassical possible mechanisms for edge transport
Carbon is the dominant impurity species with lithium coatings

- Measured lithium concentration is much less than carbon
  - Carbon concentration ~100 times higher
  - Carbon increases when lithium coatings are applied
  - Neoclassical effect: higher Z accumulates, low Z screened out

- Increase in $n_C$ due to lack of ELMs
  - Can be mitigated by triggering ELMs

R. Bell
M. Bell, PPCF 51 (2009) 124054