Scrape-off layer turbulence (SOLT) simulations of effects of lithium deposition on heat flux characteristics observed in NSTX*

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Acknowledgement:
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American Physical Society
Division of Plasma Physics

Denver CO, November 11-15, 2013

*Work supported by DOE grant DE-FG02-02ER54678.

Abstract

Established benefits of lithium conditioning observed in experiments at NSTX [1] include reduced ELMs, improved energy confinement and lowered H-mode thresholds. Recent measurements of the power exhaust channel [2] found reduced heat flux width (λ) at the divertor, compared to experiments with no lithium coating. Gradients of plasma energy and particle density as well as density fluctuations are observed to be reduced at the edge in the presence of lithium [3], suggesting a role for interchange-driven turbulence in setting heat flux characteristics in these experiments. To explore this possibility, we simulate the edge turbulence, in the outboard midplane, driven by plasma profiles measured in two NSTX experiments, with and without lithium, using the SOLT model code, [4] newly expanded [5] to include *self-consistent* ion diamagnetic drift evolution. Simulated and experimentally measured heat flux and λ are compared, and the underlying (simulated) turbulence is characterized.

[1] R. Maingi et al., Nucl. Fusion **52**, 083001 (2012).
[2] T.K. Gray et al., IAEA 2012, San Diego, paper EX/P5-27.
[3] J.M. Canik et al., Phys. Plasmas **18**, 056118 (2011).
[4] J.R. Myra et al., Phys. Plasmas **18**, 012305 (2011).
[5] D.A. Russell et al., Bull. Am. Phys. Soc., DPP 2012, **57** (12), BP8-159.

Outline

- **SOLT model equations**
  - self-consistent evolution of ion pressure and ion diamagnetic drift
- **Input to SOLT from experiments**
  - pre- and post-lithium deposition edge density and temperature profiles
- **SOLT results**
  - matching total power with the experiments
- **SOL power (P_{SOL}) and SOL heat flux width (λ) for ions and electrons**
- **Turbulence at power-matching**
  - density fluctuation spectra, heat flux profiles, mean poloidal flows
- A **structure velocity** for SOLT blobs
  - comparison with mean flows
- **Flow damping** (damping the mean vorticity)
  - effect on structure velocity and heat exhaust
- **Validation possibilities**
- **Conclusions**

SOLT Model Equations

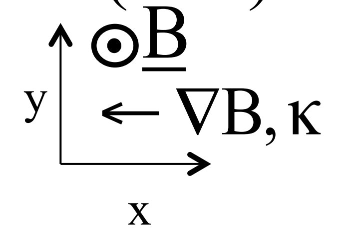
The SOLT code now includes the self-consistent evolution of
ion pressure and **ion diamagnetic drift**.

- Generalized vorticity is evolved; **the Boussinesq approximation has been dropped**.
- The new equations of evolution are consistent with the **drift-ordered, reduced-Braginskii fluid equations** derived by Simakov and Catto [6] and used in the BOUT code. [7]
- A new multi-grid algorithm extracts the electro-static potential from the vorticity.

Generalized Vorticity (ρ)

Bohm units

2D (OM)



$$\rho + \nabla\cdot(n\nabla\phi + \nabla p_i) = 0$$

$$(\partial_t + v_E\cdot\nabla)\rho = -2b\times\kappa\cdot\nabla(p_e + p_i) - J_{||} + \mu\nabla^2\rho - \nu_{\bar{\rho}}\bar{\rho} + \frac{1}{2}\left[n v_{di}\cdot\nabla\nabla^2\phi\right] - \frac{1}{2}\left[v_E\cdot\nabla(\nabla^2 p_i) - \nabla^2(v_E\cdot\nabla p_i)\right] - \frac{1}{2}b\times\nabla n\cdot\nabla v_E^2$$

$p_{e,i} = nT_{e,i}$, $v_E = b\times\nabla\phi$, and $v_{di} = b\times\nabla p_i / n$ is the ion diamagnetic drift

[6] A.N. Simakov and P.J. Catto, Phys. Plasmas **10**, 4744 (2003).
[7] M.V. Umansky et al., Comp. Phys. Comm. **180**, 887 (2009).

SOLT Model Equations (cont.)

Density (quasi-neutral) $$(\partial_t + v_E \cdot \nabla)n = J_{//,n} + D_n \nabla^2 n + S_n$$

Electron Temperature $$(\partial_t + v_E \cdot \nabla)T_e = q_{//,e} / n + D_{Te} \nabla^2 T_e + S_{Te}$$

Ion Temperature $$(\partial_t + v_E \cdot \nabla)T_i = q_{//,i} / n + D_{Ti} \nabla^2 T_i + S_{Ti}$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + v_E \cdot \nabla, \quad v_E = \hat{b} \times \nabla\phi \quad (\hat{b} \cdot \nabla \times v_E = \nabla^2 \phi), \nabla = \nabla_\perp$$

$J_{//}$ models electron drift waves on the closed field lines and sheath physics, through closure relations, in the SOL.

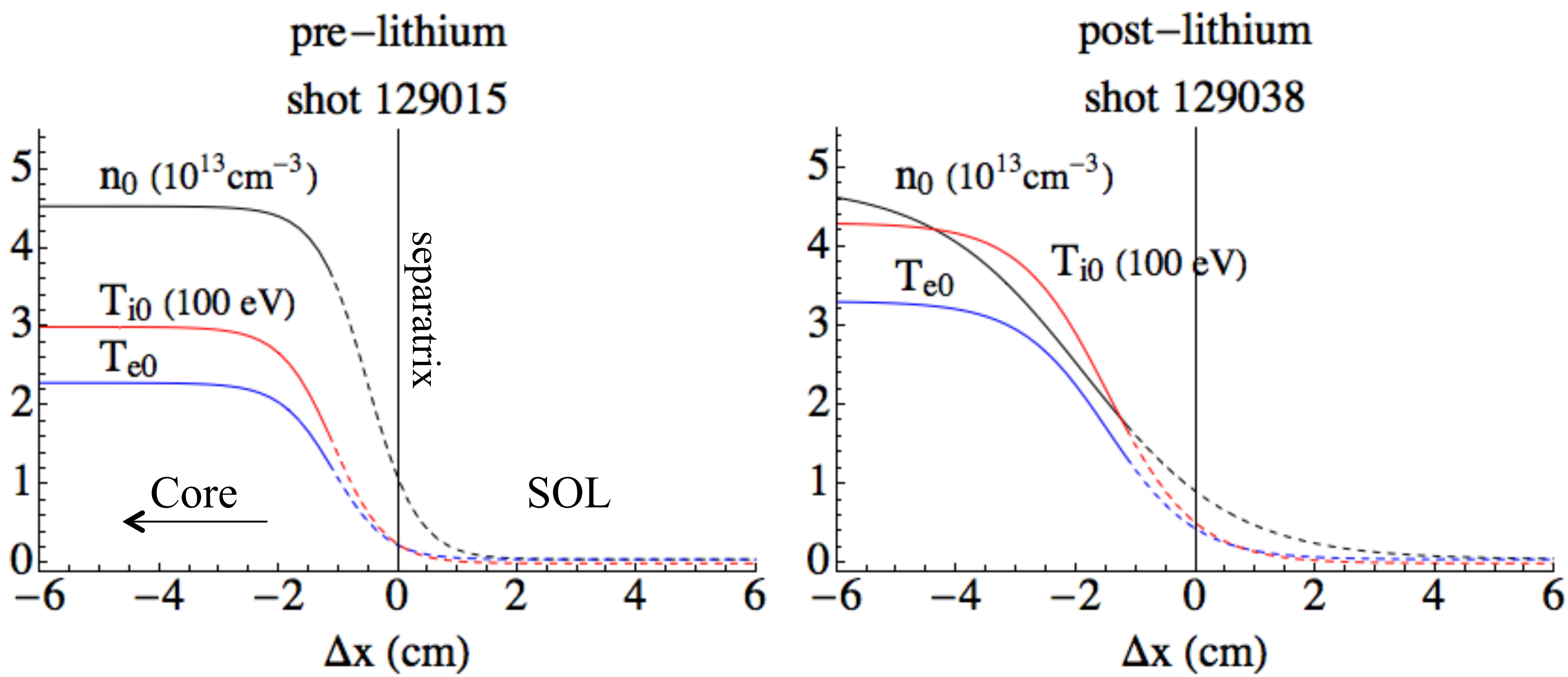
$q_{//}$ models heat flux in the SOL. [8]

All fields are turbulent: $n = n(x,y,t)$, etc.
We do not expand about ambient profiles in SOLT.
Self-consistent O(1) fluctuations are supported.

[8] J.R. Myra et al., Phys. Plasmas **18**, 012305 (2011).

Input to SOLT from experiment

- **Experimental profiles** are fitted to tanh reference profiles near the separatrix.



- Simulation profiles relax to these <u>on the core side</u> ($\Delta x < 0$) <u>only</u>, at rates that vanish monotonically as $\Delta x \rightarrow 0^{(-)}$.

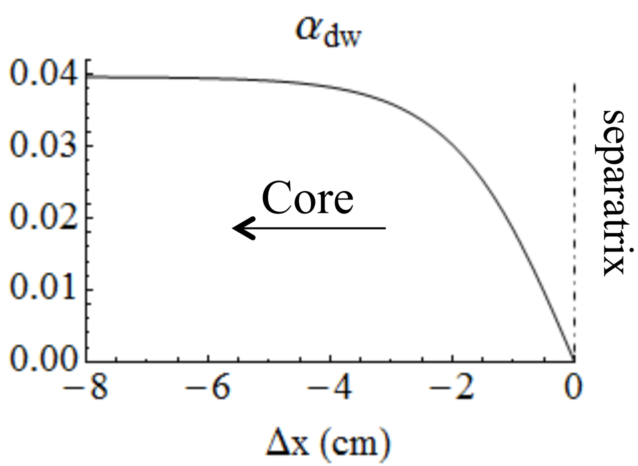
$$S_n = \nu_n(x)\cdot(n_0(x)-n),\;\; S_{Te,Ti} = \nu_{Te,Ti}(x)\cdot(T_{e0,i0}(x)-T_{e,i})$$

$$\nu_{all}(\Delta x)\xrightarrow{\Delta x \rightarrow 0^{(-)}} 0$$

Input to SOLT (cont.)

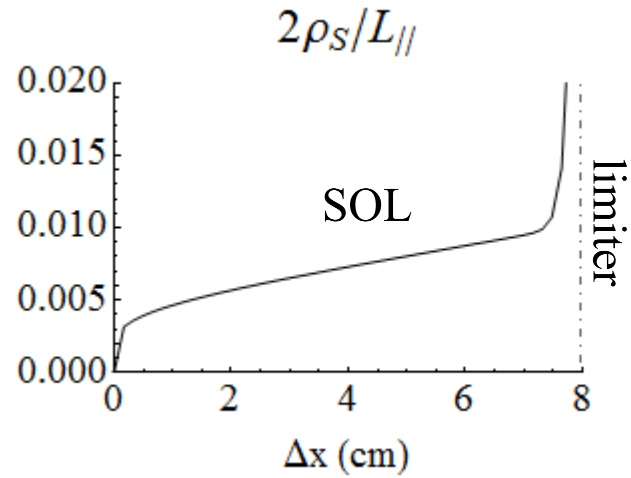
- **Other SOLT profiles and parameters**

- **adiabaticity enforcer**
for drift waves ($J_{//}$)
inside the separatrix



$$\alpha_{dw}(\Delta x \to -\infty) = 2(\Omega_e / \nu_{ei})\rho_S^2 / (q_B R)^2$$

- **connection length**
for sheath physics
($J_{//}$ and $q_{//}$) in the SOL



- **reference parameters** for both shots:

$D\ plasma, B = 3416\,G$

$physical\ units:$

$T_{ref} = 100\ eV, c_S = 69.2\ km/s$

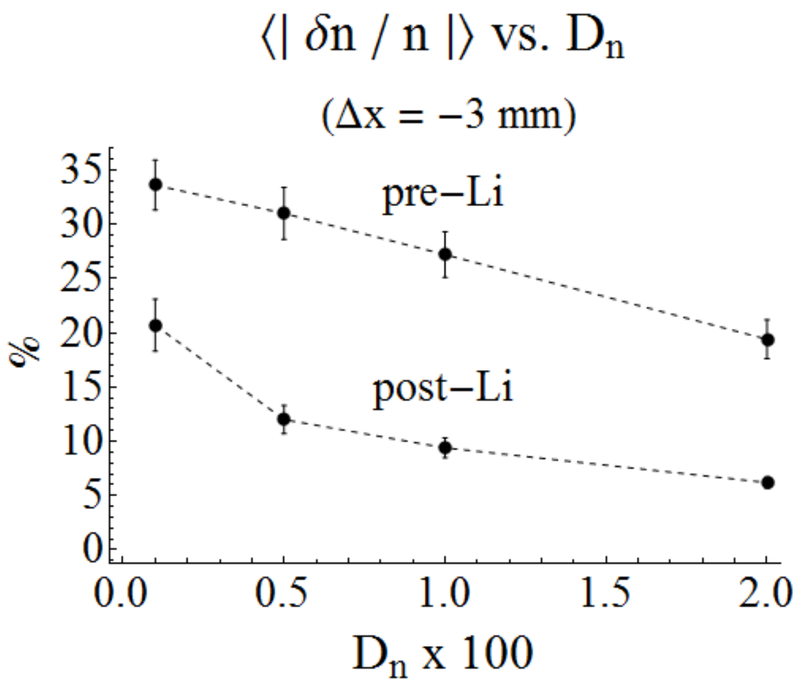
$\Omega_i / 2\pi = 25.7\,MHz$

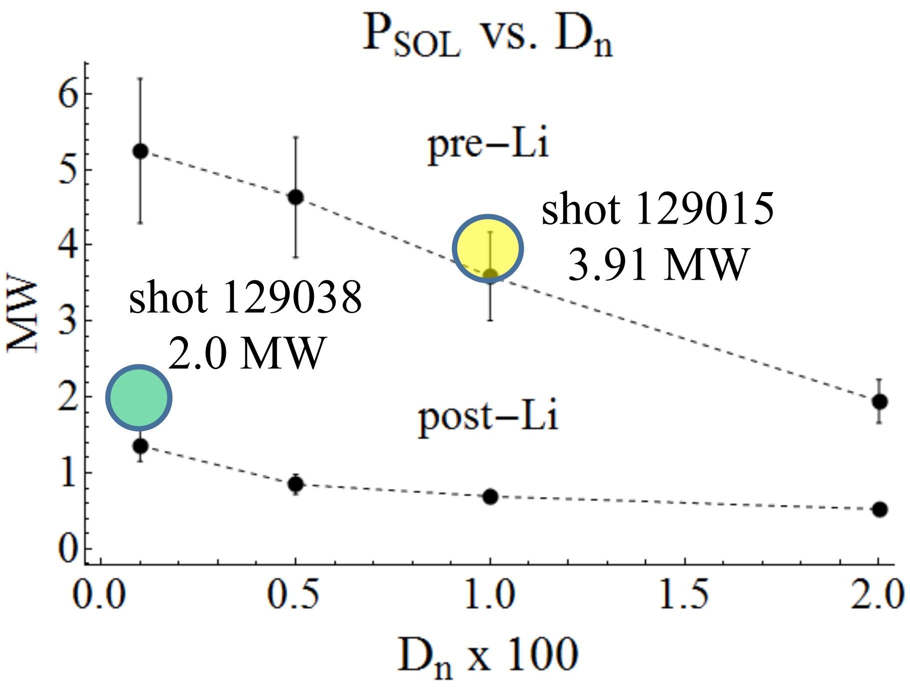
$\rho_S = c_S / \Omega_i = 4.23\ mm$

SOLT Results

SOLT's turbulence (P_{SOL} and λ) depends on physical parameters for which experimental values are not available *a priori* (e.g. μ , $\nu_{\bar{\rho}}$, $D_{n,Te,Ti}$).

- SOLT can recover some experimental observations (P_{SOL}, e.g.) for reasonable choices.

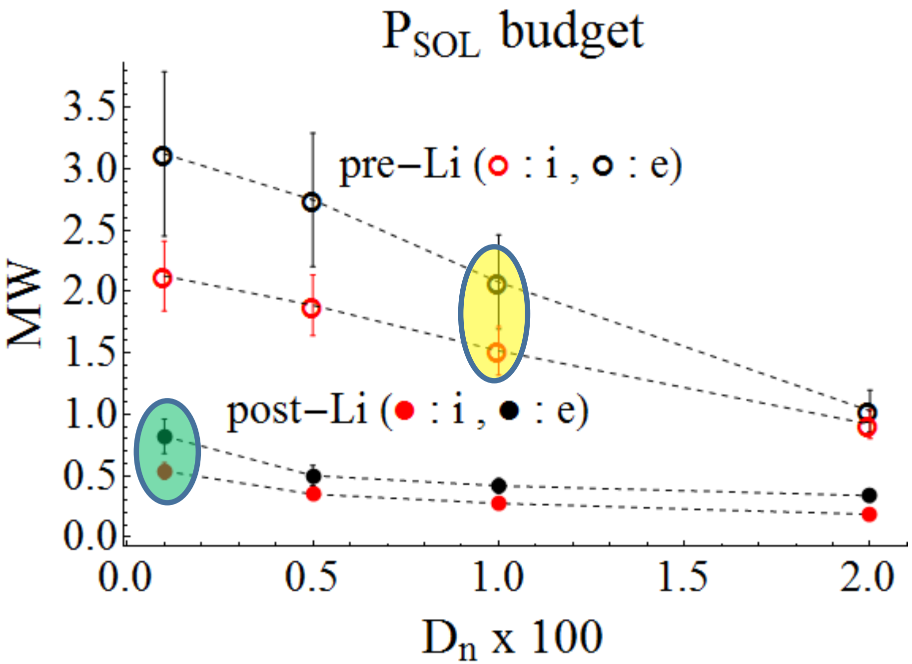




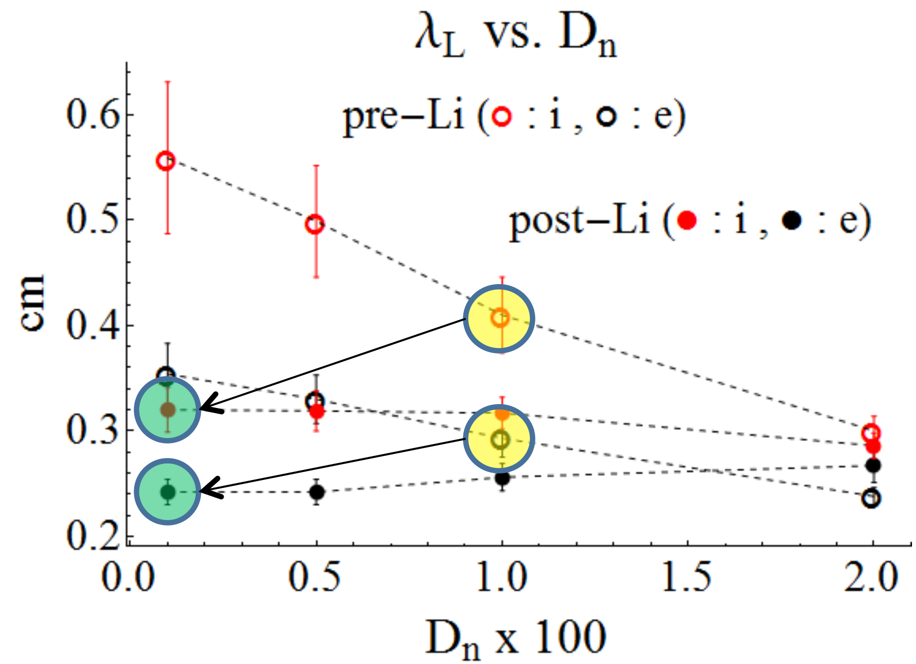
- Drift-interchange turbulence is weaker for the broader, post-Li profiles.
- Turbulent (blob) heat transport is weaker for the broader, post-Li profiles.

P_{SOL} and heat flux width λ for ions and electrons

Ion / Electron Power Budget



SOL heat-flux width (Loarte)



- Ion and electron contributions to P_{SOL} are comparable at the shot total powers (ovals).

- At the shot powers (circles), post-lithium footprints are smaller than pre-lithium footprints (arrows), with values within the range of experimental observation.
- Ions have the larger footprint.

$$\lambda_{Loarte} = P_{SOL} / [q_{//}(\Delta x \rightarrow 0^{(+)}) \cdot 2\pi R B_{\theta} / B]$$

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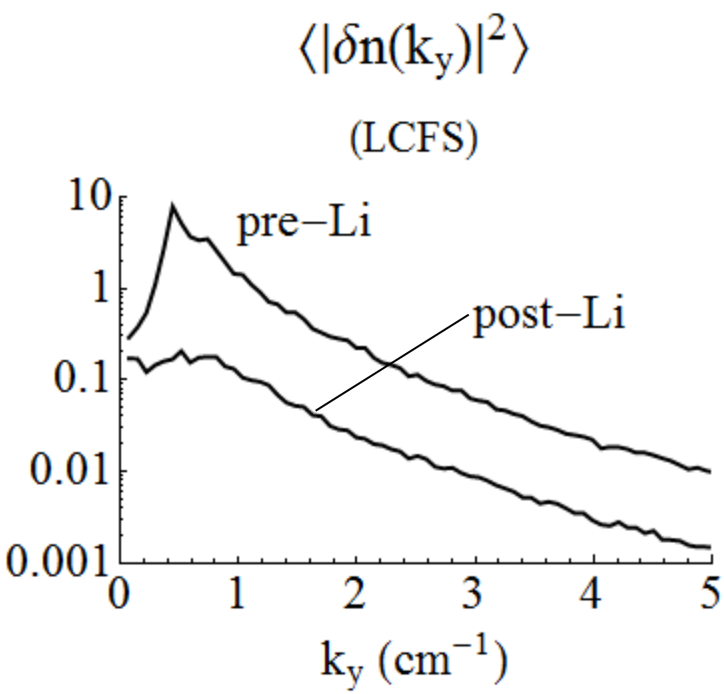
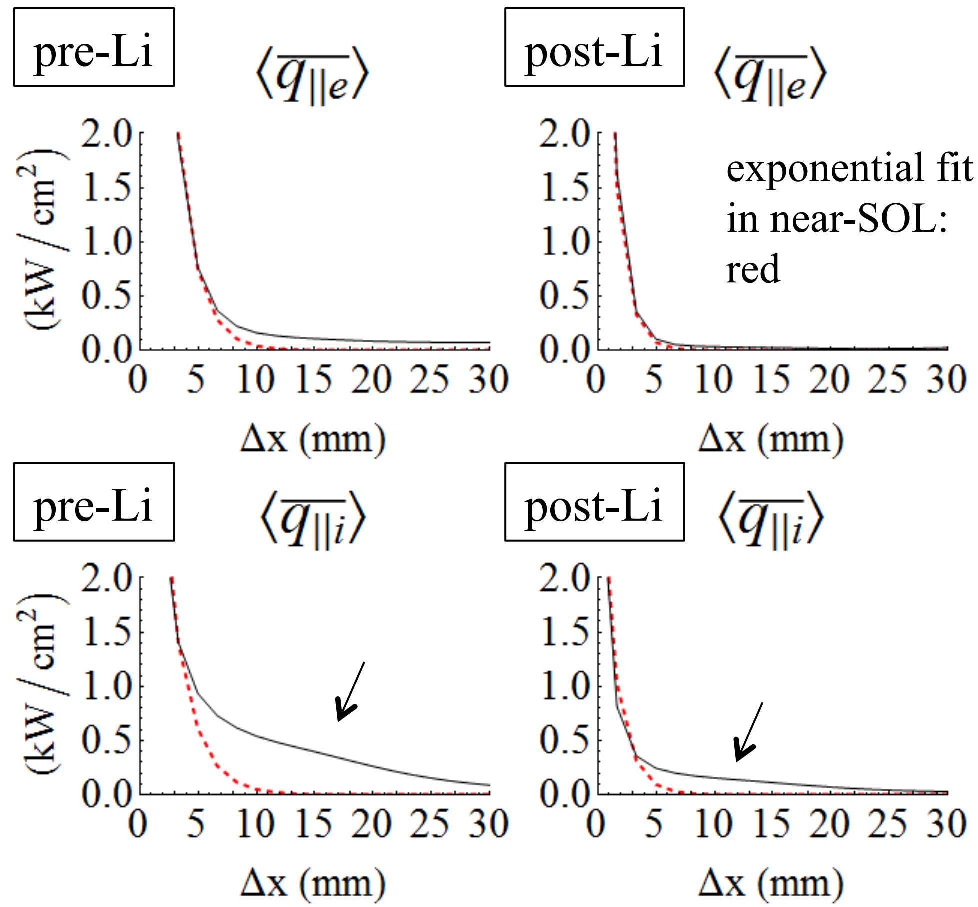
SOLT turbulence at power-matching

Density Fluctuation Spectra



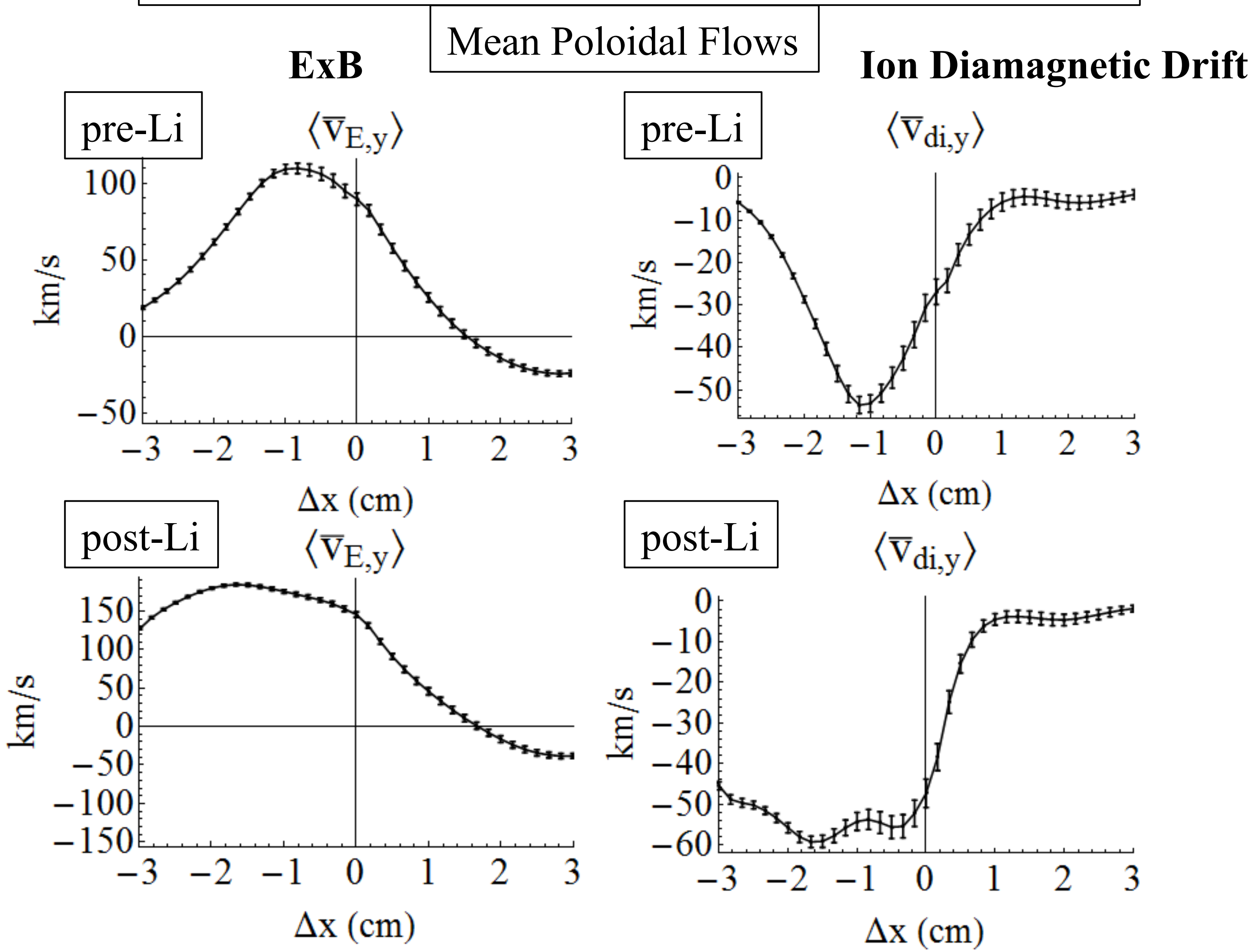
- Post-Li density fluctuations at the separatrix are weaker across the spectrum, in qualitative agreement with reflectometry measurements. [S. Kubota, private communication and NP8.00020 this meeting.]

Heat Flux Profiles



- Ions have pronounced super-exponential tails, compared to electrons. Tails are reduced, post-Li.

SOLT turbulence at power-matching (cont.)



- These flows are much larger than the poloidal turbulent structure velocities (2-3 km/s) observed near the (putative) separatrix with gas-puff imaging (GPI). [9]

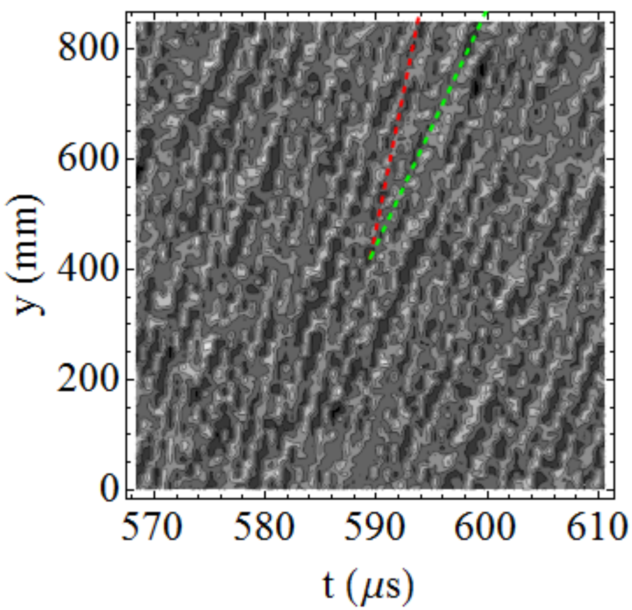
[9] B. Cao et al., Plasma Phys. Control. Fusion **54**, 112001 (2012).

Synthetic Structure Velocity for SOLT
for comparison with GPI velocities

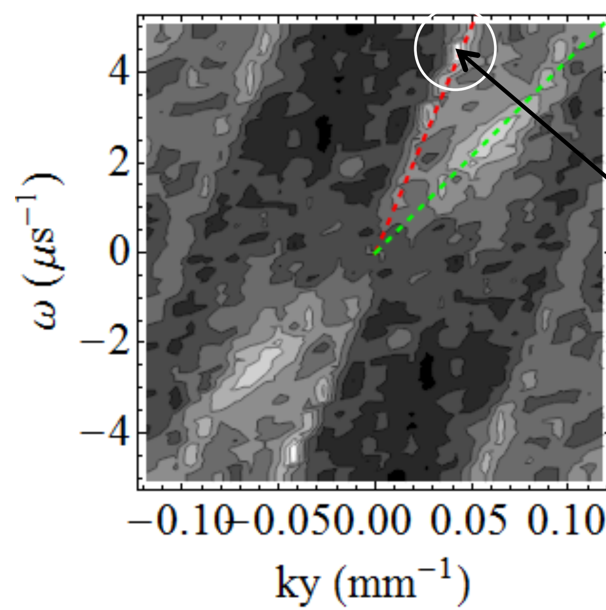
Do blobs go with the flow?

Density tracks in (y,t)-space have linear counterparts in (ky,ω)-space.
Two sets of tracks are evident near the separatrix.

$\delta n(\Delta x = 0, y, t)$



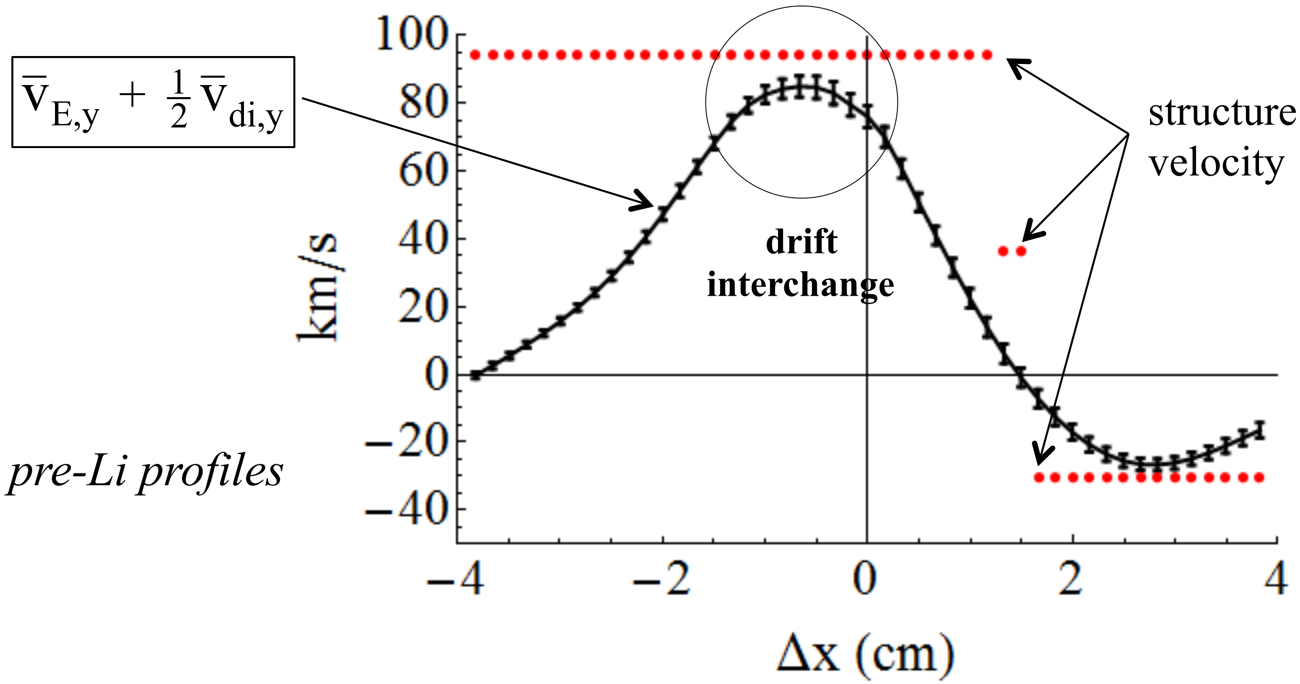
$\left|\delta n(\Delta x = 0, ky, \omega)\right|^2$



Structure
Velocity:
ω/ky
@
power
maximum

At each Δx, we take the **structure velocity** to be that of the dominant (red) track, i.e., **the phase velocity at the global maximum of the power spectrum**.

Structure Velocity and Flow



pre-Li profiles

Cziegler et al. [10] experiments on Alcator C-Mod reveal similar transitions.

- The structure velocity (red) is constant on radial intervals.

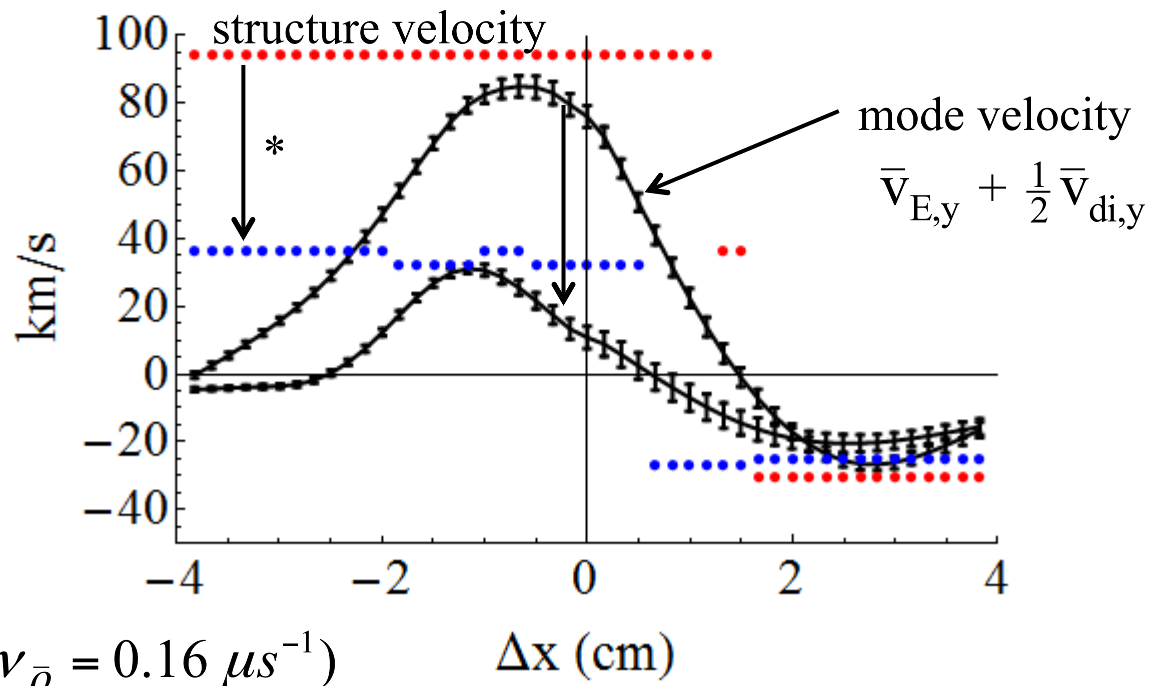
Modes localized to radial zones underlie the turbulence.

- **drift-interchange mode's** phase (and group) velocity: $v_E + \frac{1}{2} v_{di}$ $\approx$ the structure velocity near the separatrix.

- *Without flow damping*, SOLT's structure velocities can be 50x observed GPI poloidal velocities [9], depending on radial location.

[10] I. Cziegler et al., Phys. Plasmas **17**, 056120 (2010).

Flow Damping reduces Structure Velocities



pre-Li profiles

$*(\nu_{\bar{\rho}} = 0.16\ \mu s^{-1})$

Damping the mean vorticity, $\bar{\rho} = -\partial_x \left\langle \mathrm{n}\ \partial_x \phi + \partial_x \mathrm{p_i} \right\rangle_x$, $\partial_t \bar{\rho} = -\nu_{\bar{\rho}} \cdot \bar{\rho}$

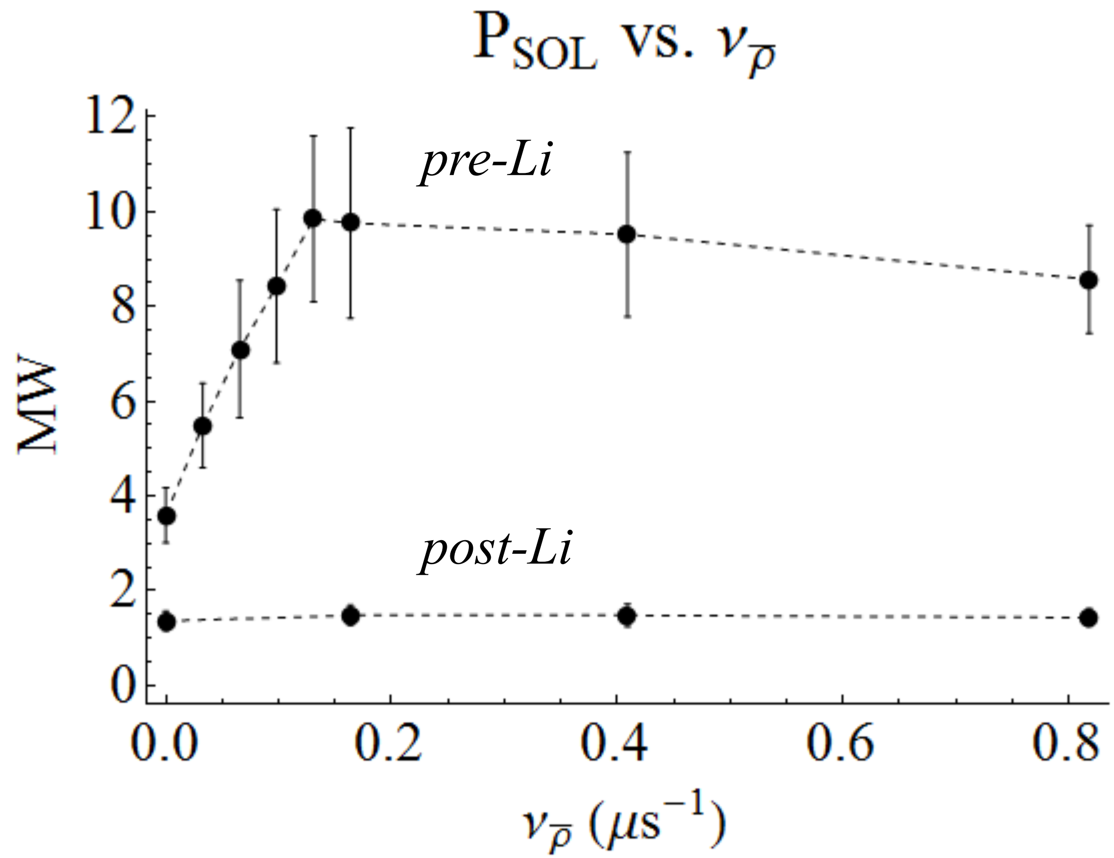
(charge-exchange flow-damping by neutrals, e.g.)

- reduces the mode velocity *and the structure velocity* near the separatrix
- encourages $\mathrm{V_E} \rightarrow -\mathrm{V_{di}}$:

  measured shot profiles: $\mathrm{v_{di}} \cong -50$ km/s (Δx = −1 cm)

  $\Rightarrow$ structure velocities → 25 km/s with flow damping, near the separatrix.

Flow Damping and Heat Exhaust



- Flow damping raises heat exhaust in pre-Li profiles.
- The shear rate is controlling the turbulence in pre-Li profiles.
- Post-Li profiles are relatively immune to flow damping.
- *Profile steepness importantly effects nonlinear dynamics*.

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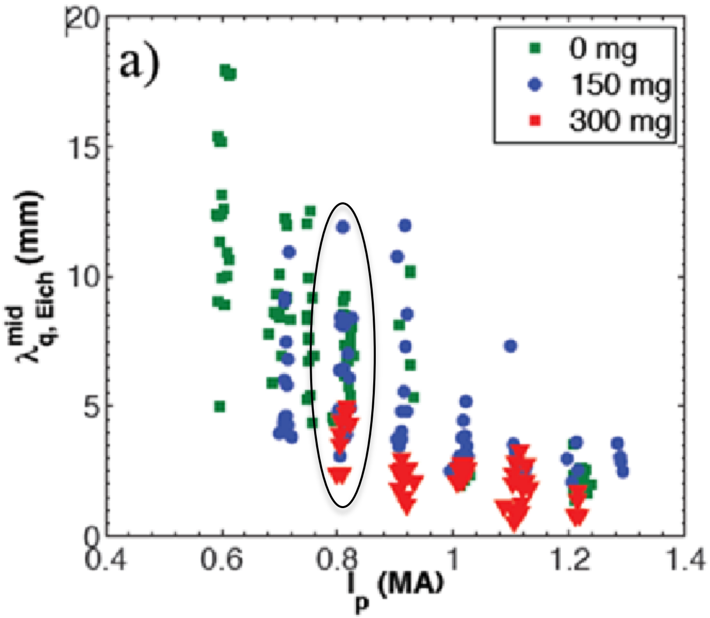
Remaining Issues / Validation Opportunities

What is the role of midplane turbulence in pre- and post-Li edge/SOL plasmas?

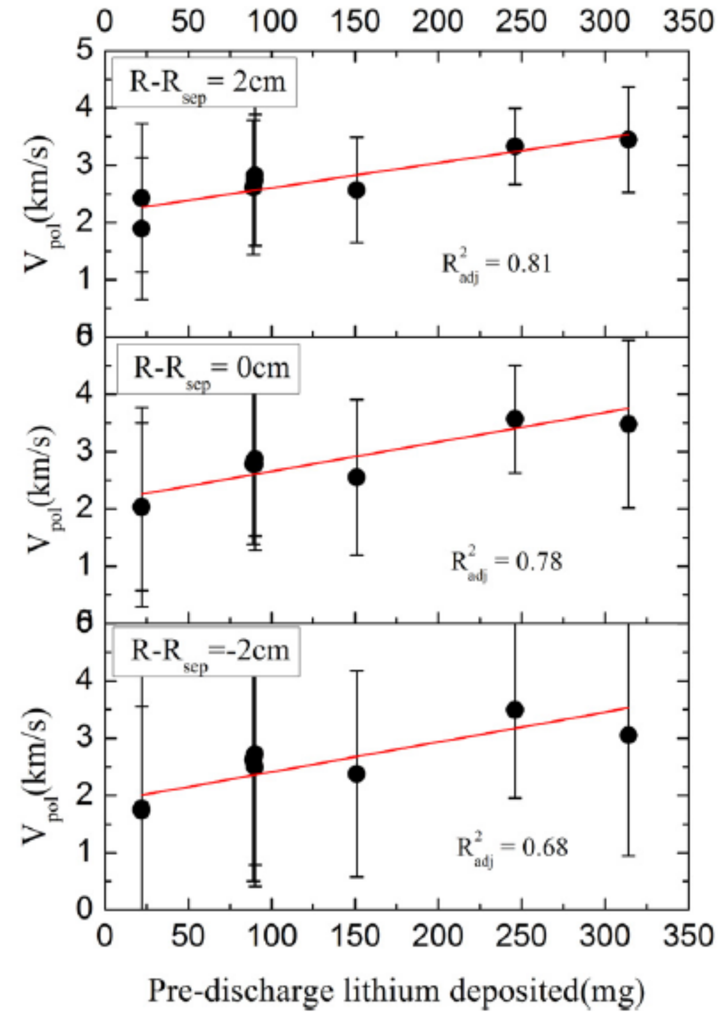
SOLT	*NSTX*
SOL heat flux width λ_q	**IRTV** [2] Fig. 7a – next slide
pre-Li: 4 mm	15 mm (simulated shot) 4 - 15 mm (database)
post-Li: 3 mm	6 mm (simulated shot) 2 - 6 mm (database)
fluctuation level δn/n	**reflectometer** [3] Fig. 8 – next slide
pre-Li: 0.3	
post-Li: 0.1 - 0.2	reduced fluctuations with Li (needs calibration)
δn drops by 10 with Li at most k	
turb. structure velocity v_y	**GPI** [9] Fig. 2 – next slide
25 km/s depending on	1 – 5 km/s
CX neutral friction;	
2 – 3 km/s in far SOL	**BES and probe comparisons also possible**
E×B flow velocity v_E	**spectroscopic data comparisons possible**
up to 100 km/s in pedestal	(~ 100 km/s typical for NSTX H-modes)

NSTX Data

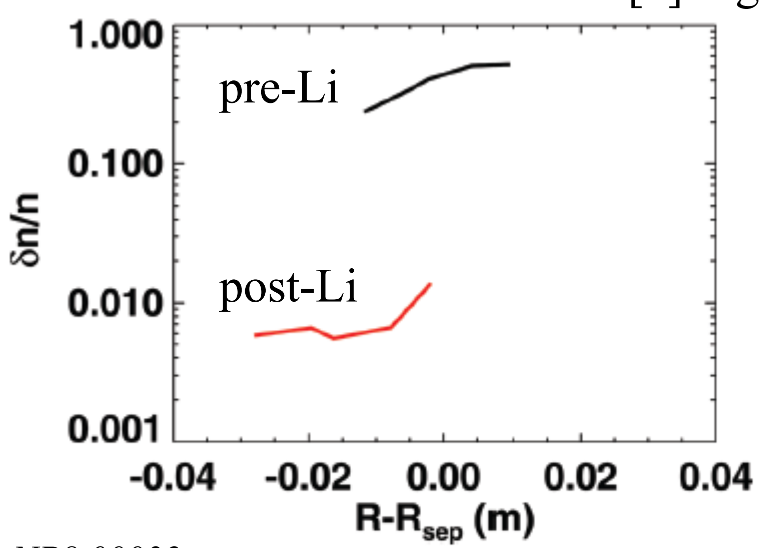
IRTV
T.K. Gray et al. [2] Fig. 7



GPI
B. Cao et al. [9] Fig. 2



Reflectometer
J.M. Canik / S. Kubota et al. [3] Fig. 8



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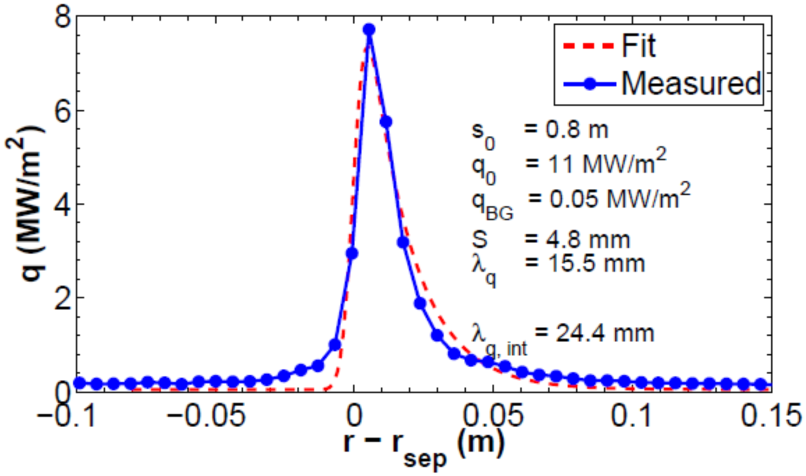
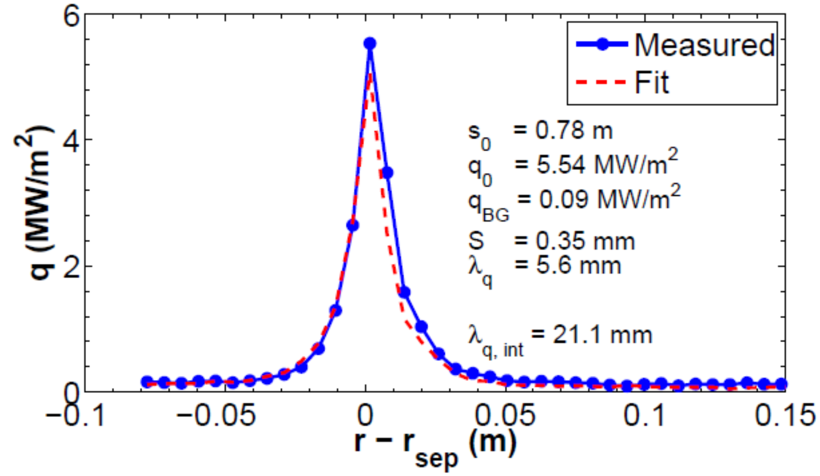
NSTX Data (cont.)

IRTV
T.K. Gray
(unpublished)

pre-lithium
shot #129015



post-lithium
shot #129038



Conclusions

- **SOLT simulations have been compared with lithium deposition experiments on NSTX.**
- At the shot P_{SOL} values, SOLT post-lithium SOL heat-flux widths ($\lambda_{e,i}$) are smaller than pre-lithium widths with values within the range of experimental observation. Ions have larger SOL widths, $\lambda_i > \lambda_e$.
- Ion and electron contributions to P_{SOL} are comparable at shot total powers.
- Post-lithium density fluctuations at the separatrix are weaker across the spectrum, in qualitative agreement with reflectometry measurements.
- A synthetic **structure velocity** reveals blob poloidal speeds near the separatrix that are close to the phase velocity ($v_E + ½\, v_{di}$) expected of drift-interchange modes (including ion diamagnetic effects).
- **Modes localized to radial zones underlie the turbulence.**
- **Flow damping reduces SOLT structure velocities, approaching GPI values.**
  - Damping encourages $v_E \rightarrow (-)v_{di}$.
  - Structure velocities near the separatrix ~ Max($v_E + ½\, v_{di}$).
- GPI poloidal velocities of 2-3 km/s , within ± 2 cm of the separatrix, are *feasible* in simulations *outside* the separatrix, near the sheath-engendered flow-reversal point.

Were the reported GPI velocities in fact measured farther out in the SOL?