Modeling the Effect of Lithium on SOL Dynamics and the SOL Heat Flux Width Observed in NSTX

D.A. Russell, D.A. D'Ippolito and J.R. Myra
Lodestar Research Corporation, Boulder, CO, USA

J.M. Canik and T.K. Gray
Oak Ridge National Laboratory, Oak Ridge, TN, USA

S.J. Zweben
Princeton Plasma Physics Laboratory, Princeton, NJ, USA

Presented at the
IAEA Fusion Energy Conference
St. Petersburg, Russian Federation
13-18 October 2014

Work supported by USDOE grants DE-FG02-97ER54392 and DE-FG02-02ER54678.

Outline

- **SOLT model equations**
    - self-consistent evolution of ion pressure and ion diamagnetic drift
- **Input to SOLT from experiments**
    - pre- and post-lithium (Li) deposition edge density and temperature profiles

      Profiles drive the turbulence; Li physics is taken for granted.
- **Matching the SOL power (P_{SOL}) with the experiments**
- **SOL Heat Flux Profile Width (λ_q)**
    - simulations recover the experimental trend: Li reduces λ_q
- **SOLT Turbulence Characteristics**
    - density fluctuation spectra, mean poloidal flows
- **A Structure Velocity for SOLT Blobs**
    - comparison with mean poloidal flows
- **Flow damping** (damping the mean vorticity)
    - effect on structure velocity and heat exhaust
- **SOLT / Experiments comparison**
- **Conclusions**

SOLT Model Equations

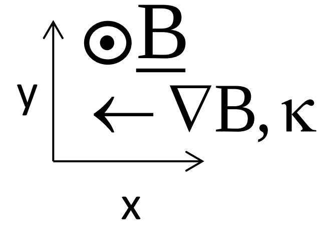
The SOLT code now includes the self-consistent evolution of
ion pressure and **ion diamagnetic drift**.

- 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* and used in the BOUT code.**
- A new multi-grid algorithm extracts the electro-static potential from the vorticity.

Generalized Vorticity (ρ)

Bohm units

2D (OM)



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

$$(\partial_t + v_E \cdot \nabla)\rho = -2 b \times \kappa \cdot \nabla (p_e + p_i) - J_{//} + \mu \nabla^2 \rho - \nu_{\bar{\rho}} \bar{\rho} +$$

$$+ \frac{1}{2}\left[n v_{di} \cdot \nabla \nabla^2 \phi \right] - \frac{1}{2}\left[v_E \cdot \nabla(\nabla^2 p_i) - \nabla^2 (v_E \cdot \nabla p_i) \right] - \frac{1}{2} b \times \nabla n \cdot \nabla v_E^2$$

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

*A.N. Simakov and P.J. Catto, Phys. Plasmas **10**, 4744 (2003).

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.

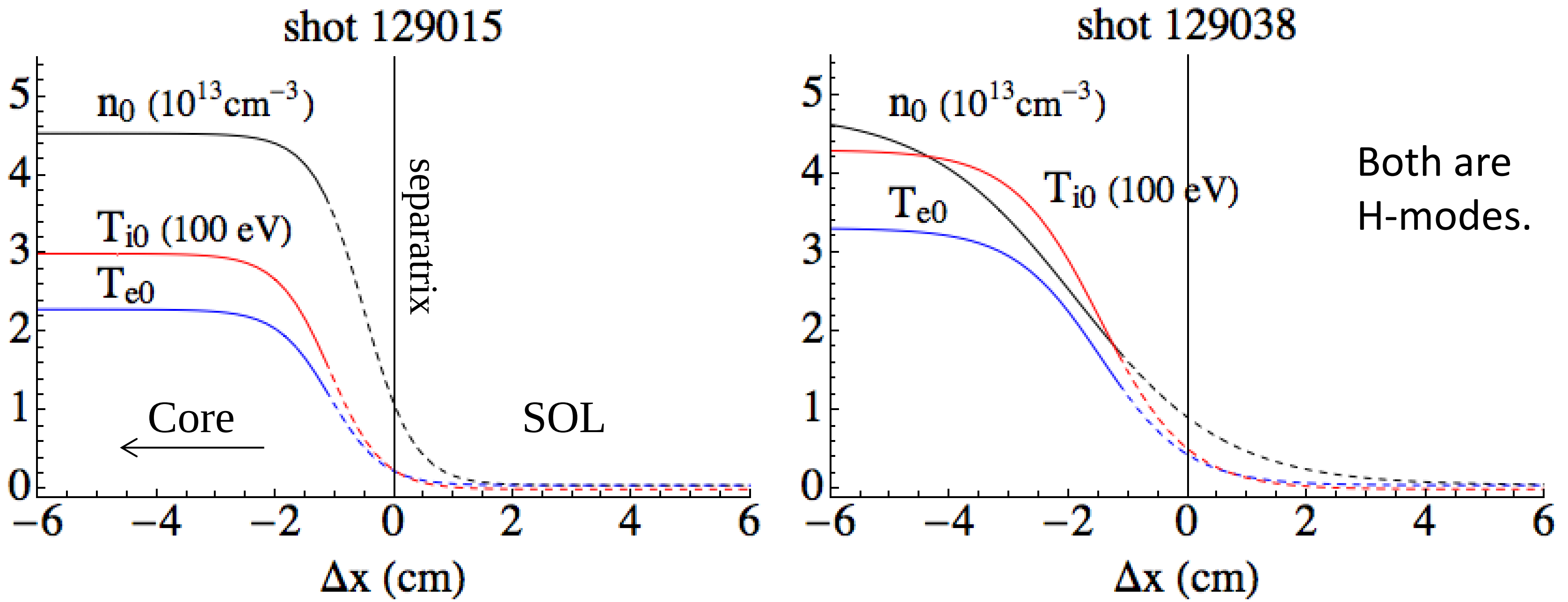
$q_{//}$ models heat flux in the SOL.*

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.

* 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.



pre-Li

with-Li

Both are H-modes.

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

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

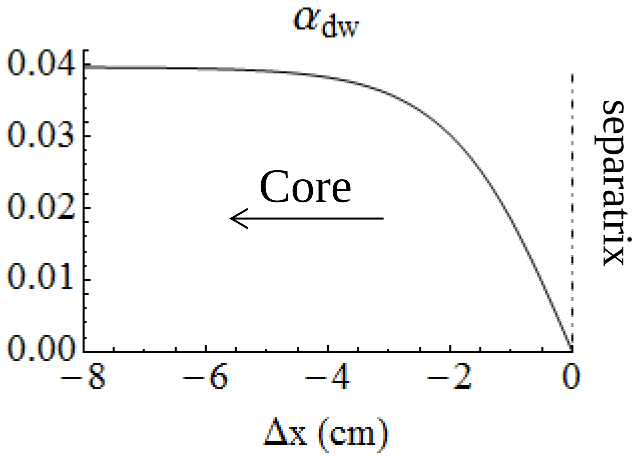
$$\nu_{all}(\Delta x)\xrightarrow{\Delta x \rightarrow 0^{(-)}} 0$$

Input to SOLT (cont.)

- **Other SOLT profiles and parameters**

- **adiabaticity**

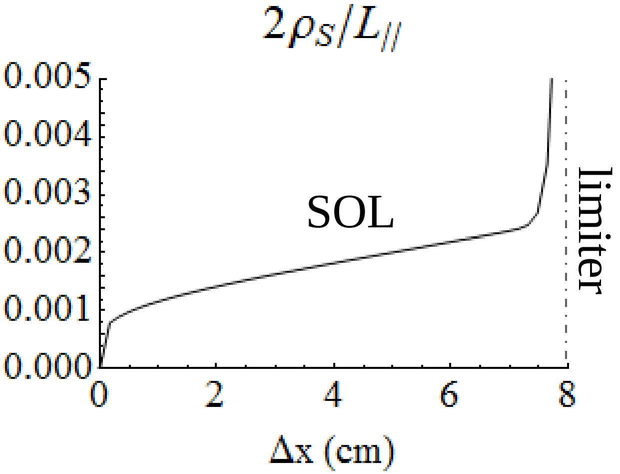
for drift waves ($J_{//}$)
inside the separatrix



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

- **connection length**

for sheath physics
($J_{//}$ and $q_{//}$) in the SOL



- **reference parameters** for both shots:

$D\ plasma,\ B = 3.42\ kG$

$physical\ units:$

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

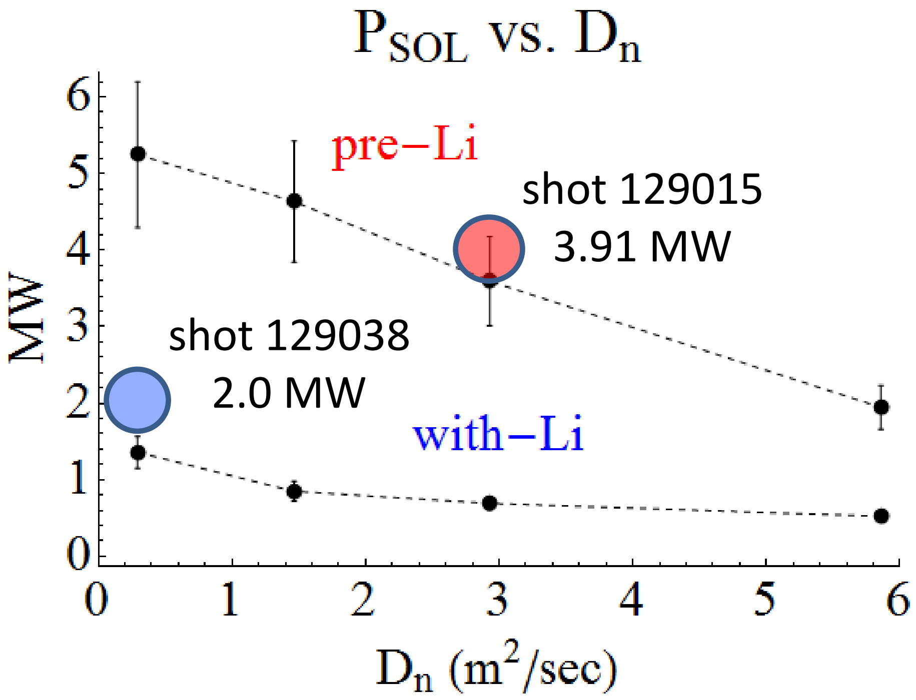
$\Omega_i / 2\pi = 2.57\,MHz$

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

SOLT Results

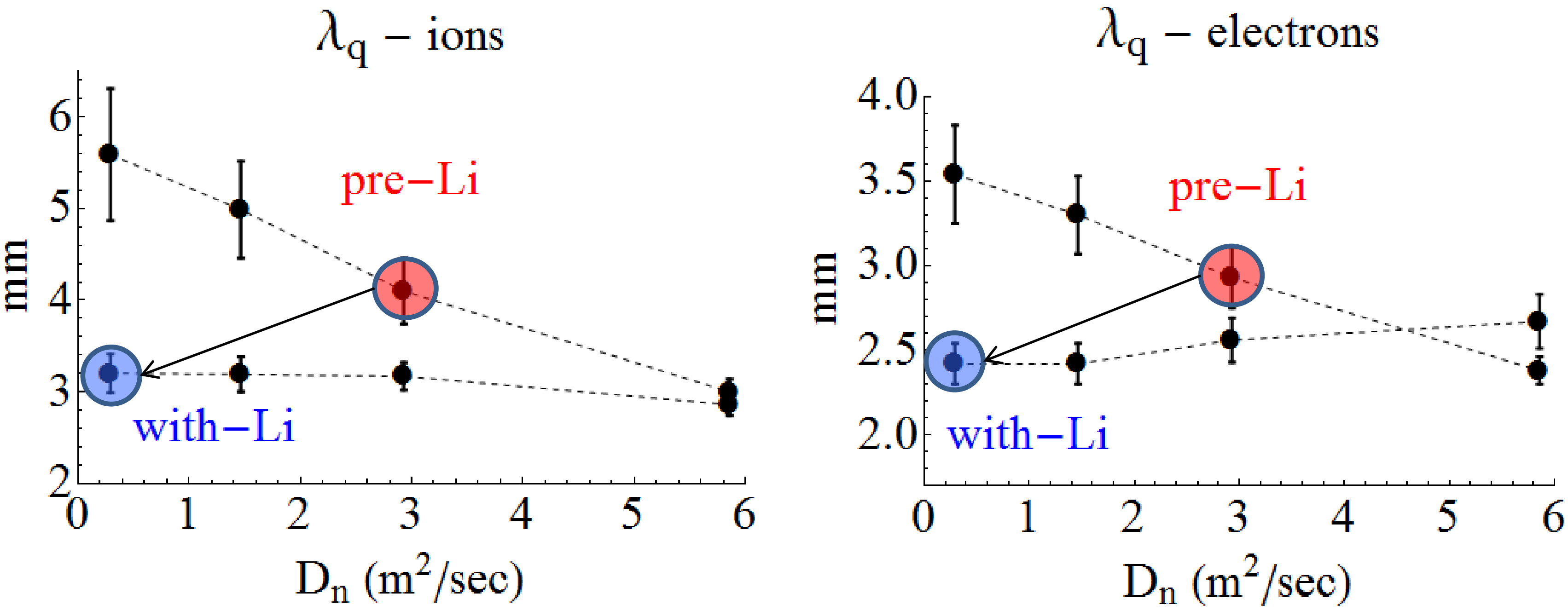
SOLT's turbulence (P_{SOL} and λ_q) depends on physical parameters for which experimental values are not available *a priori* (e.g. μ , $\nu_{\bar{\rho}}$, $D_{n,Te,Ti}$).

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



- ***Power-Matching*** : we adjust the density diffusion coefficient (D_n) so that SOLT's turbulent P_{SOL} matches that measured in the experiment (circles).

SOL Heat Flux Width λ_q at Power-Matching

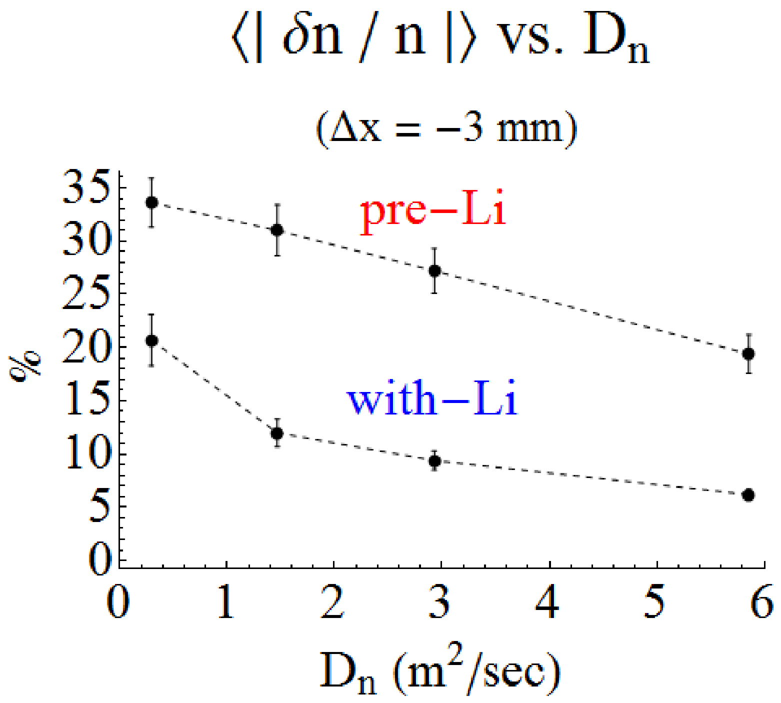


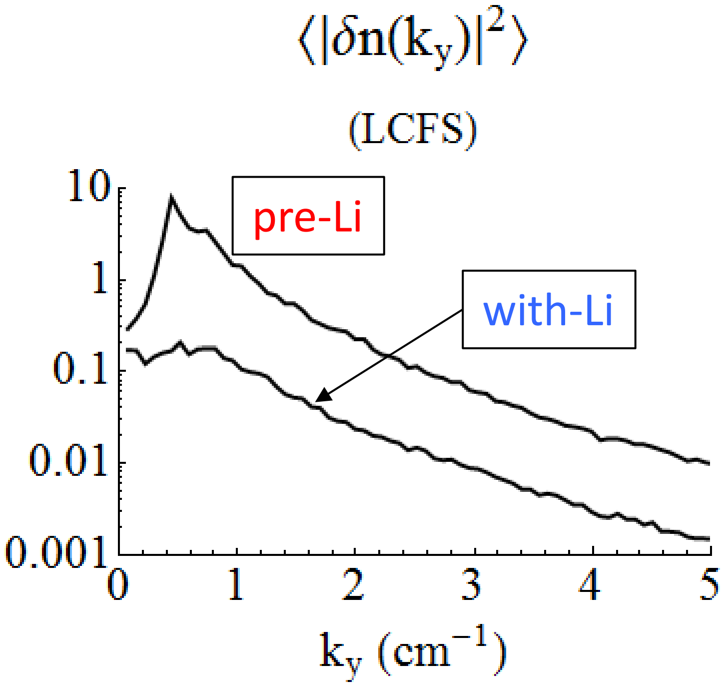
- **At the shot powers** (circles), with-Li λ_q is smaller than pre-Li λ_q .
- This pre-Li / with -Li trend agrees with experiment.

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

(*This definition* : *A. Loarte*)

SOLT Turbulence





- Diffusion is not driving the heat flux; it's damping the turbulence, which drives the heat flux.

- With-Li: density fluctuations at the separatrix are weaker across the spectrum, in qualitative agreement with reflectometry measurements. [S. Kubota, private communication.]

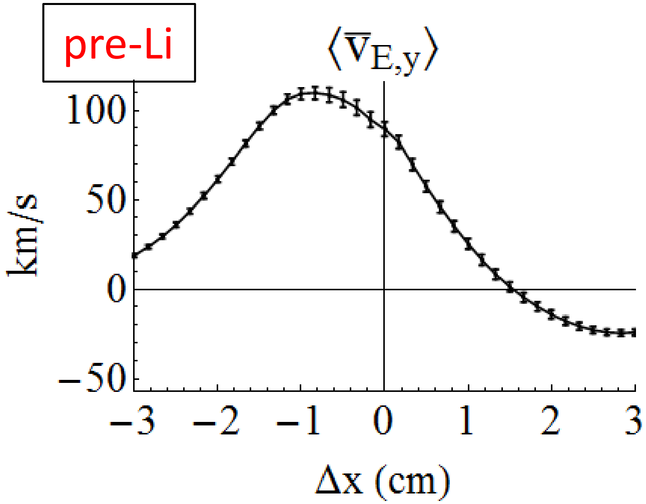
Drift-interchange turbulence is weaker for the broader, with-Li profiles.

⇓

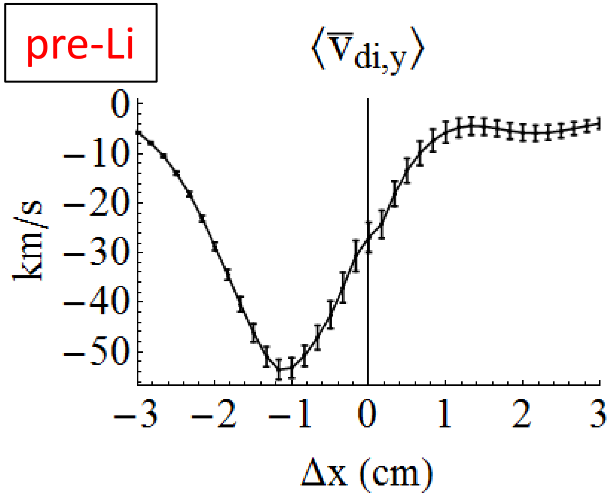
Turbulent (blob) heat transport is weaker for the broader, with-Li profiles.

SOLT Mean Poloidal Flows

ExB



Ion Diamagnetic Drift



- These SOLT mean flow velocities are much larger than the poloidal turbulent *structure* (blob) velocities (2-3 km/s) observed near the separatrix with gas-puff imaging (GPI).*

- Are the experimental *mean flow* velocities similarly far removed from the SOLT mean flow velocities? How do blobs move in the background flow?

- Implications for flow-shear moderation of turbulent transport.

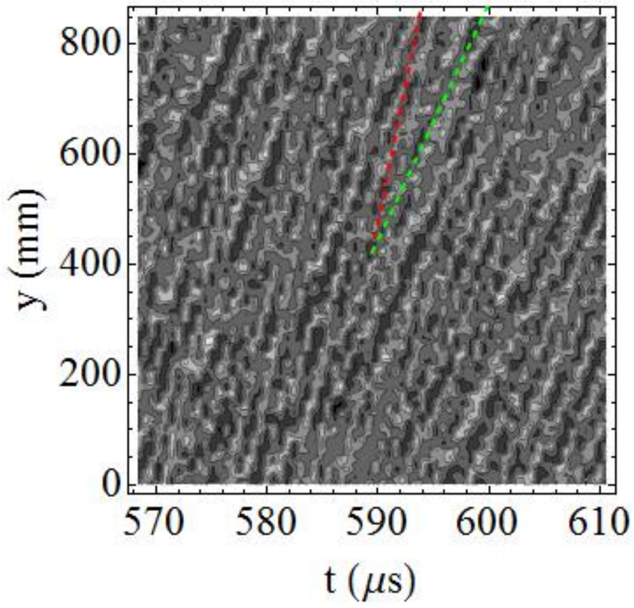
*B. Cao et al., Plasma Phys. Control. Fusion **54**, 112001 (2012).

Synthetic Structure Velocity for SOLT
for comparison with GPI velocities

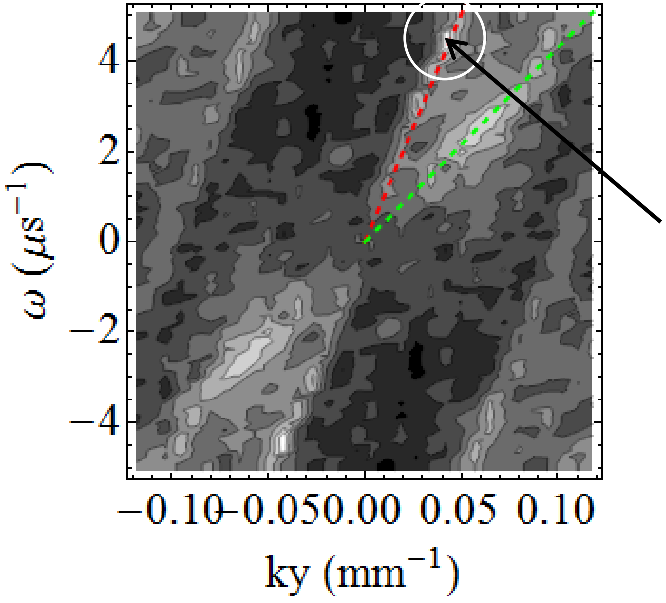
Do blobs go with the flow?

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

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



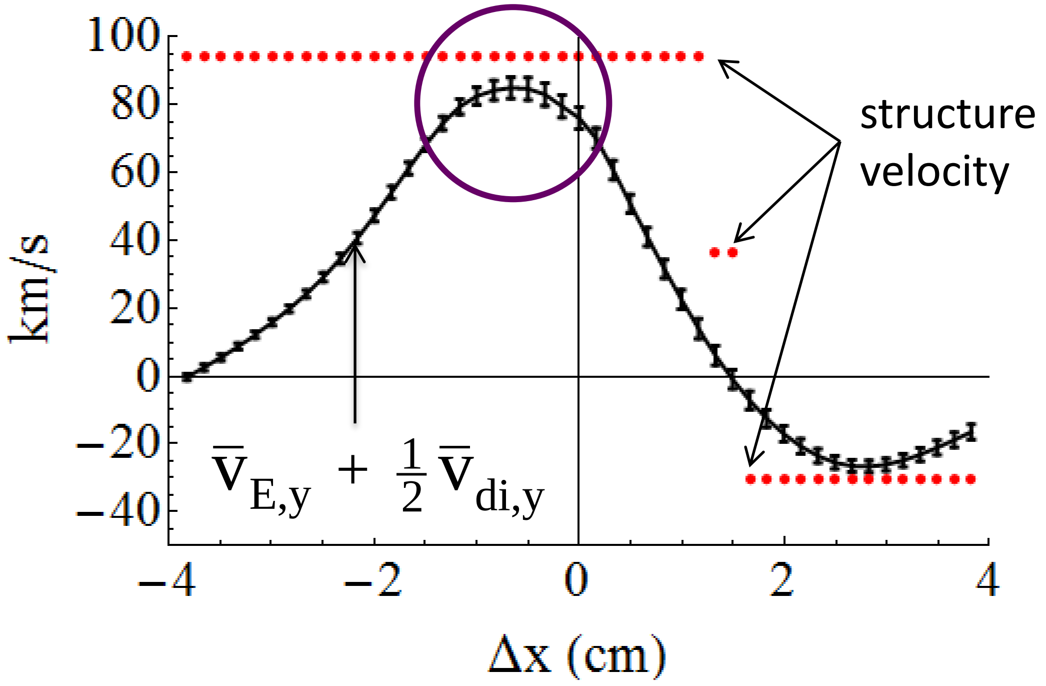
$$\left|\delta n(\Delta x = 0, ky, \omega)\right|^2$$



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



ion diamagnetic modified interchange mode

Cziegler et al. * 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**.
- Ion-diamagnetic-modified interchange mode:
  phase (and group) velocity: $v_E + ½ v_{di}$
  ≈ the structure velocity near the separatrix.
- SOLT's structure velocities can be 50x observed GPI poloidal velocities, depending on radial location, *without flow damping.*

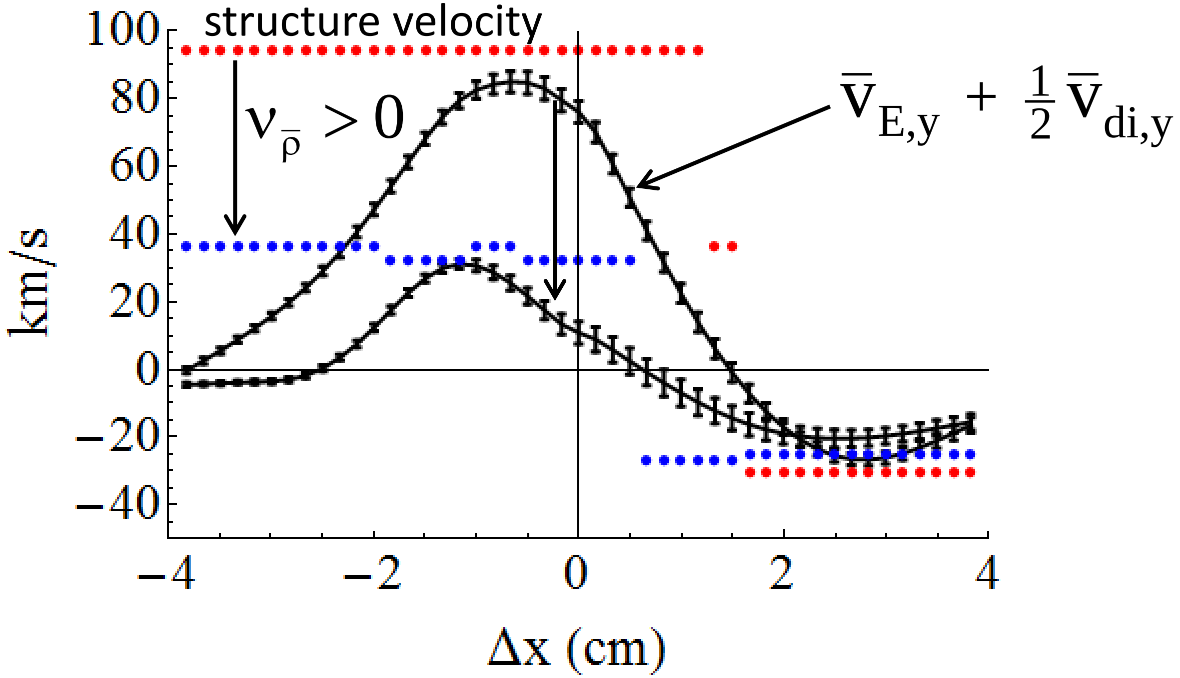
* I. Cziegler et al., Phys. Plasmas **17**, 056120 (2010).

Flow Damping Reduces Structure Velocities

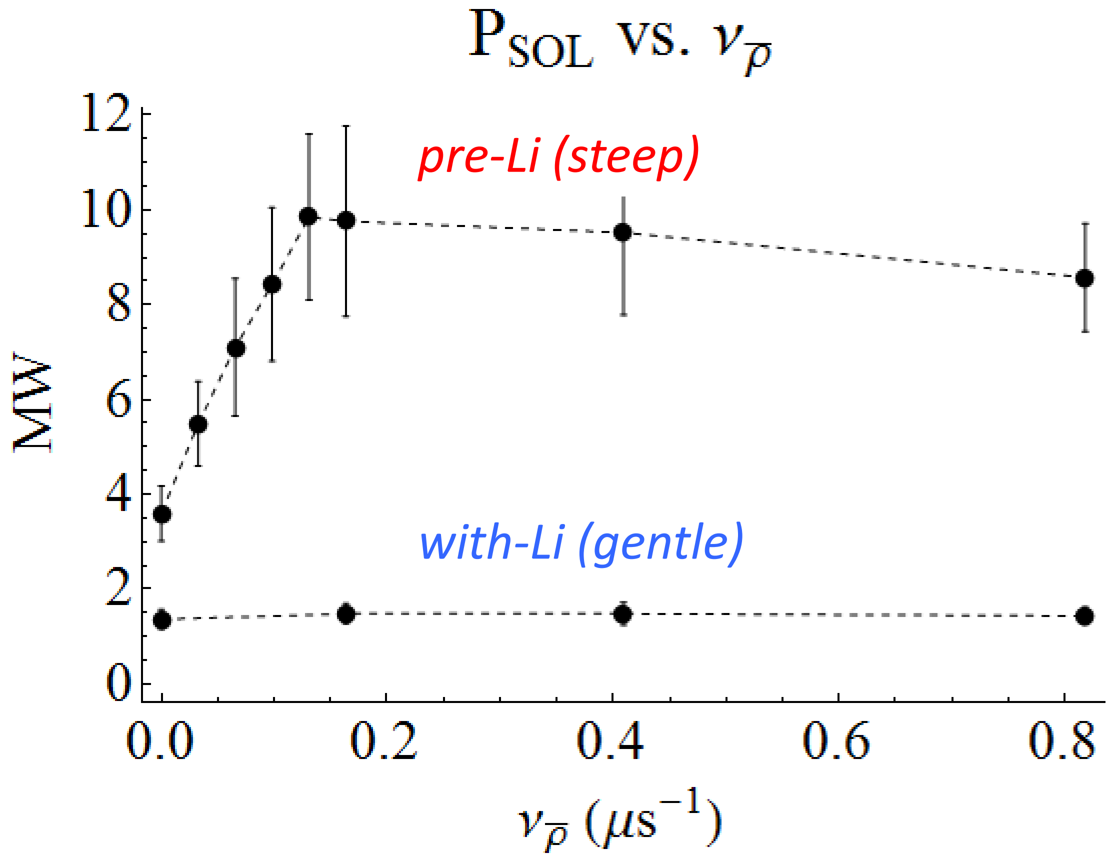
$$\partial_t \bar{\rho} = -\nu_{\bar{\rho}} \cdot \bar{\rho} + \ldots, \quad \bar{\rho} = -\partial_x \left\langle n\, \partial_x \phi + \partial_x p_i \right\rangle_y = -\partial_x \left\langle n\, v_{E,y} + n\, v_{di,y} \right\rangle_y$$

Damping the mean vorticity (charge-exchange flow-damping by neutrals, e.g.)

- encourages $\mathbf{v}_E \rightarrow -\mathbf{v}_{di}$
- reduces the mode velocity *and the structure velocity* 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.
- With-Li profiles are relatively immune to flow damping.
- *Profile steepness importantly effects nonlinear dynamics*.

SOLT / Experiment Comparisons

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

Conclusions

- **SOLT simulations are compared with lithium deposition experiments on NSTX.**
- **SOLT heat-flux widths with Li are smaller than pre-Li widths**.

  This trend agrees with experimental observations.

- **SOLT density fluctuations with-Li are weaker across the spectrum,**

  in qualitative agreement with reflectometry measurements.

- **Simulated structure velocity near the separatrix ~ ($v_E + \frac{1}{2} v_{di}$),**

  as expected of interchange modes modified by ion diamagnetic effects.

- **Modes localized to radial zones underlie the turbulence.**
- **Flow damping reduces SOLT structure velocities,**

  as required for agreement with GPI observations.

$$\mathrm{Li} \Rightarrow \text{gentler } \nabla \mathrm{P} \text{ (pedestal)} \Rightarrow \text{smaller turbulent } \mathrm{V}_{\perp} \Rightarrow \text{smaller } \lambda_{\mathrm{q}}$$

$$\lambda_{\mathrm{q}} \sim \mathrm{q}_{\perp} / \nabla_{//} \mathrm{q}_{//} \sim \mathrm{V}_{\perp} \mathrm{L}_{//} / \mathrm{c}_{\mathrm{S}}$$