Mean Flows and Blob Velocities in Scrape-Off Layer (SOLT) Simulations of an L-mode discharge on Alcator C-Mod*

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Abstract

Two-dimensional scrape-off layer turbulence (SOLT) code simulations are compared with an L-mode discharge on the Alcator C-Mod tokamak [M. Greenwald, et al., Phys. Plasmas **21**, 110501 (2014)]. Density and temperature profiles for the simulations were obtained by smoothly fitting Thomson scattering (TS) and mirror Langmuir probe (MLP) data from the shot. Simulations differing in turbulence intensity were obtained by varying a dissipation parameter. Mean flow profiles and density fluctuation amplitudes are consistent with those measured by MLP in the experiment and with a Fourier space diagnostic designed to measure poloidal phase velocity. Blob velocities in the simulations were determined from the correlation function for density fluctuations, as in the analysis of gas-puff-imaging (GPI) blobs in the experiment. In the *simulations*, it was found that larger blobs moved poloidally with the ExB flow velocity, v_E , in the near-SOL, while smaller fluctuations moved with the group velocity of the dominant linear (interchange) mode, $v_E + 1/2\ v_{di}$, where v_{di} is the ion diamagnetic drift velocity. Comparisons are made with the *measured* GPI correlation velocity for the discharge. The saturation mechanisms operative in the simulation of the discharge are also discussed. It is found that neither sheared flow nor pressure gradient modification can be excluded as saturation mechanisms.

Outline

C-Mod : (L-mode shot #1120711021)

- density (n_e) and electron temperature (T_e) profiles from TS and MLP
- blob velocities from correlation analysis of GPI data for the shot
- Velocity determinations using various analysis techniques (Fourier Analysis and Time-Delay-Estimations) on both MLP and GPI data are compared.

SOLT :

- simulates edge turbulence driven by the C-Mod density and T_e profiles
- examines blob velocities found in the simulations using correlation analysis of $\delta n/n$ as the proxy for comparison with GPI velocity determinations.

Primary Goals :

- determine the relationships between mean flows and blob velocities in the SOLT simulations
- compare simulated, experimental and theoretical blob velocities

Secondary Goal :

- determine saturation mechanisms in the simulations

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** used in the BOUT code.
- These are **2D electrostatic simulations** in a plane perpendicular to the **B** field in the outboard midplane region of the tokamak.

Generalized Vorticity (ρ)

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

(dynamics not shown include interchange instability)

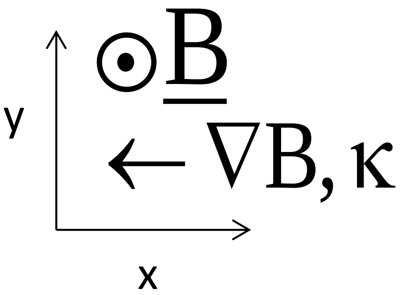
Density (n)

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

Electron Temperature (T_e)

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

2D (OM)

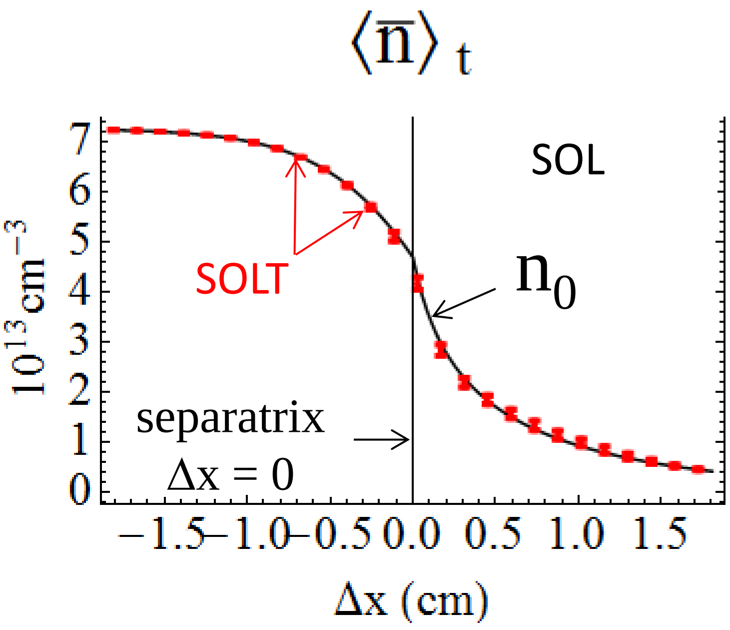


Diffusion (D_n , D_{Te}):
- dissipates high-k fluctuations
- due to physics outside SOLT
- ad hoc in practice
- sub-dominant to turbulent transport in SOLT

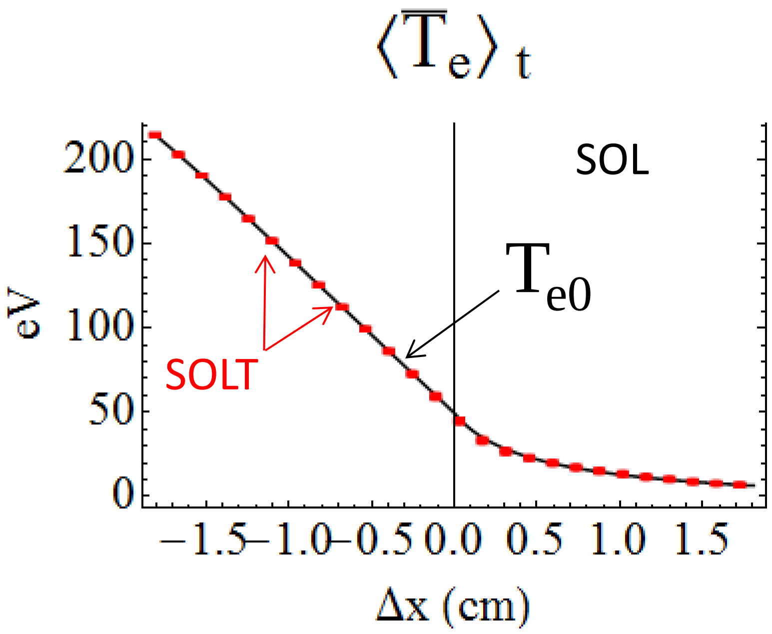
$J_{\|}$:
- electron drift waves on closed field lines
- sheath physics in the SOL

$q_{\|}$:
- heat flux in the SOL

Density and temperature reference profiles for the simulations (n_0 , T_{e0}) : smooth fits to Thomson scattering (TS) and mirror Langmuir probe (MLP) data.



$\langle \bar{n} \rangle_t$



$\langle \bar{T}_e \rangle_t$

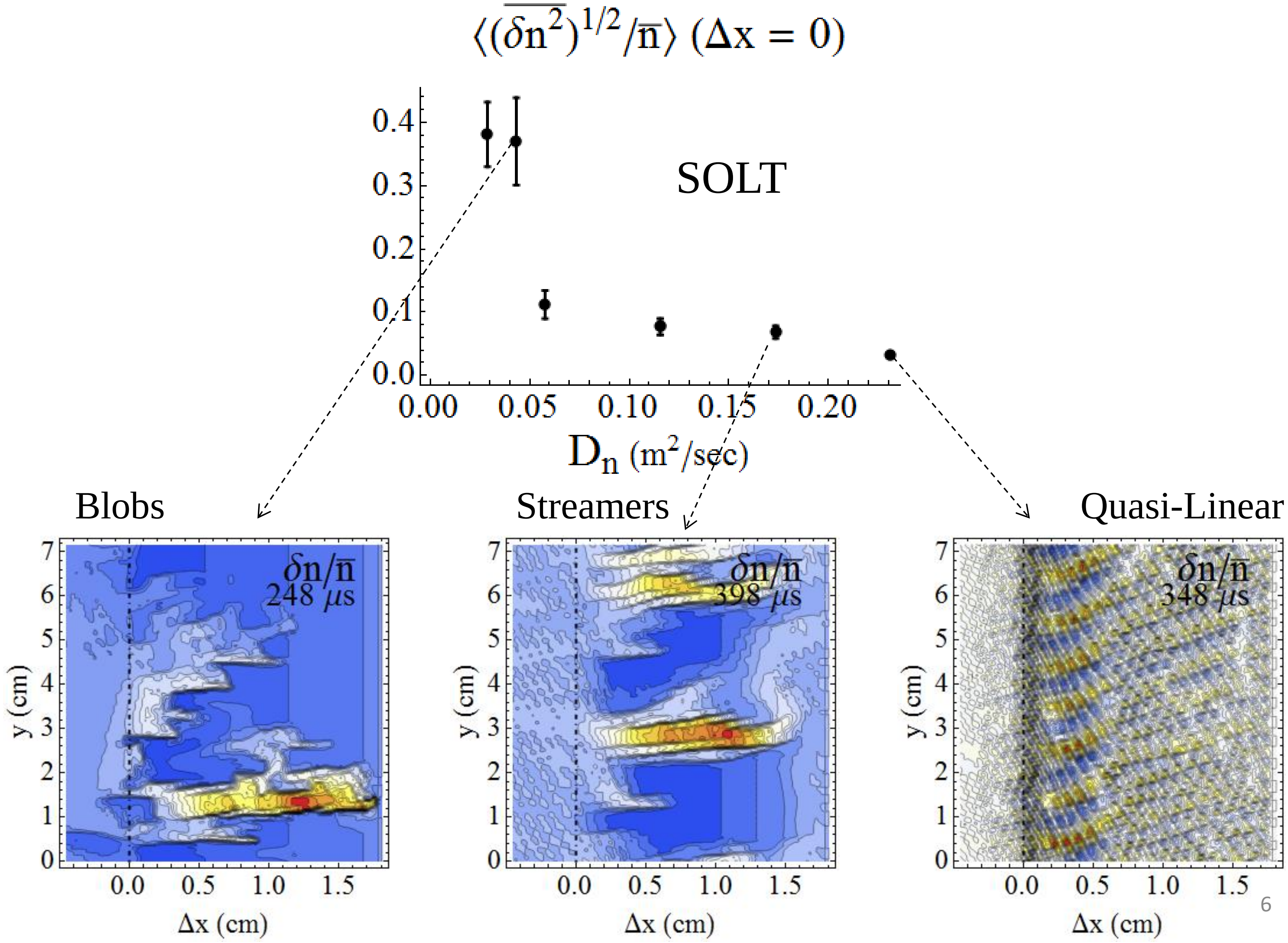
The evolving profiles in the simulations are attracted to the reference profiles by a **restorative dynamics**:

$$S_n = \nu_n (n_0 - \bar{n}) + \ldots\, ,\ \bar{n} = \langle n \rangle_y \quad (S_{Te}\text{: similar})$$

The fluctuations *are not subjected to this dynamics*.

The ion temperature was taken to be constant, $T_{i0} = T_{e0}(\Delta x = 0)$.

SOLT: δn/n is varied by changing the density diffusion coefficient D_n.



$\langle (\overline{\delta n^2})^{1/2}/\bar{n} \rangle$ ($\Delta x = 0$)

SOLT

Blobs

Streamers

Quasi-Linear

Velocities measured in SOLT simulations

V_E : ExB

V_{di} : ion diamagnetic, ~∇Pi

V_g : interchange mode group velocity, $V_E + \frac{1}{2} V_{di}$

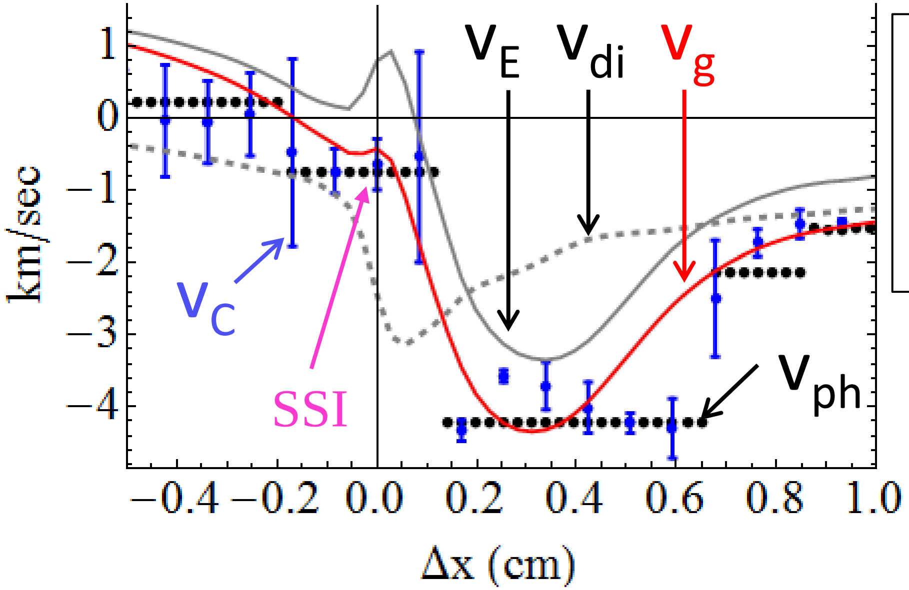
V_{ph} : poloidal phase velocity, ω/k_y , at maximum $\left|\delta n(\omega, k_y, \Delta x)\right|^2$

V_C : correlation velocity, from the location of the maximum of

$$\left\langle \delta n(x,\, y,\, t) \cdot \delta n(x+\delta x,\, y+\delta y,\, t+\delta t) \right\rangle$$

Quasi-Linear Case
$D_n = 0.23$ m^2/sec

poloidal (y)
velocities



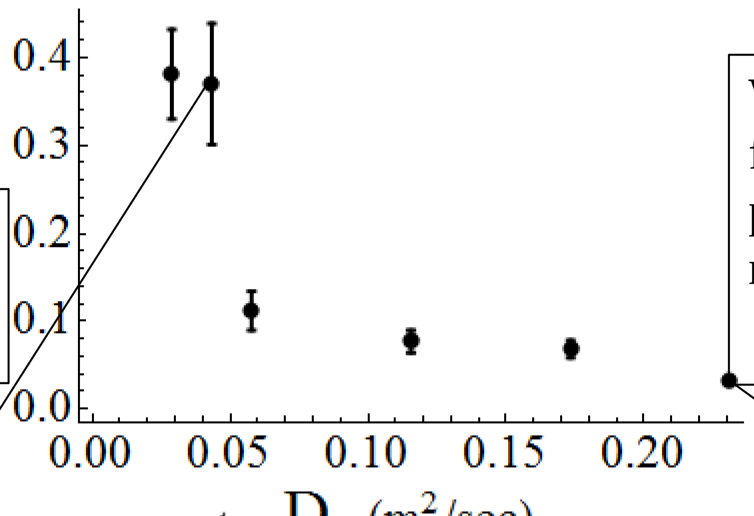
For the weaker, quasi-linear fluctuations, the interchange mode (V_g), **localized on radial zones** (V_{ph}, dots) dominates the correlation velocity (V_C).

SSI: separatrix-spanning interchange mode

SOLT poloidal velocities

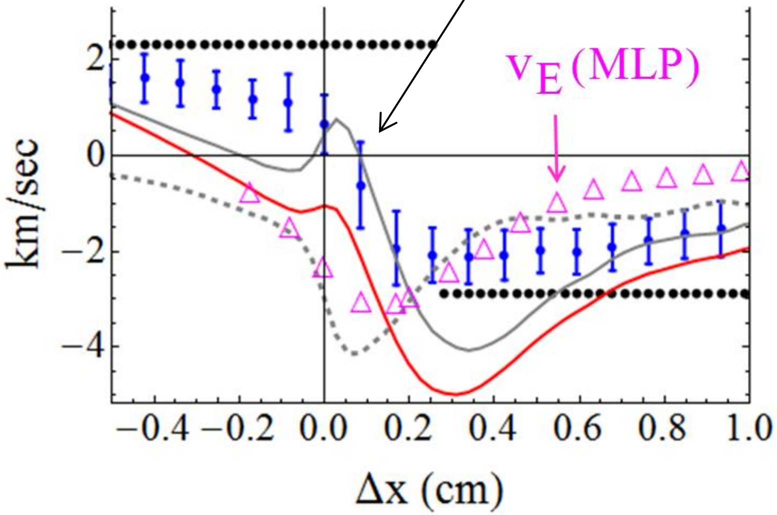
For the largest D_n, fluctuation amplitudes are small[a] and move with V_g.
For smaller D_n, amplitudes are large[b] and move with V_E.

$\langle(\overline{\delta n^2})^{1/2}/\overline{n}\rangle$ $(\Delta x = 0)$

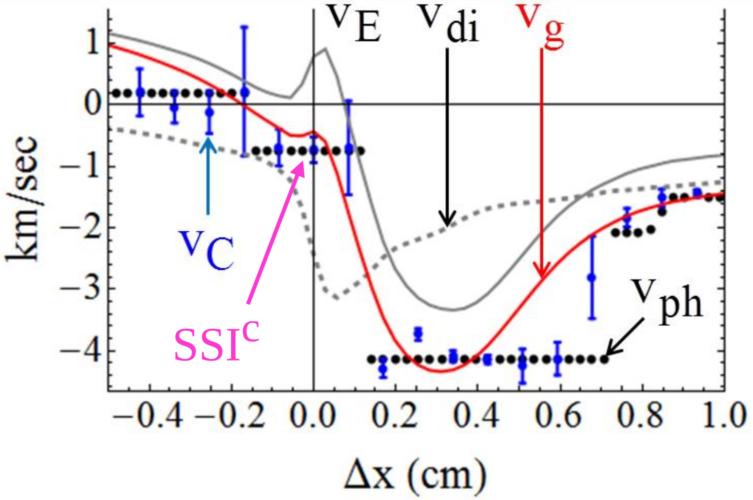


Big blobs move poloidally with V_E in the near-SOL;
$V_C \sim V_E$

Weaker, quasi-linear fluctuations move poloidally with the linear mode group velocity;
$V_C \sim V_{ph} \sim V_g$



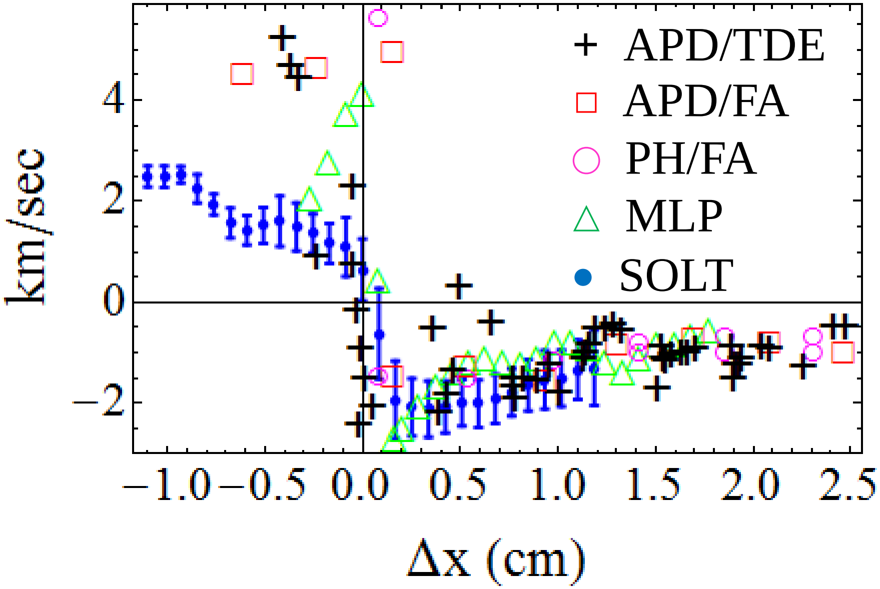
poloidal (y) velocities



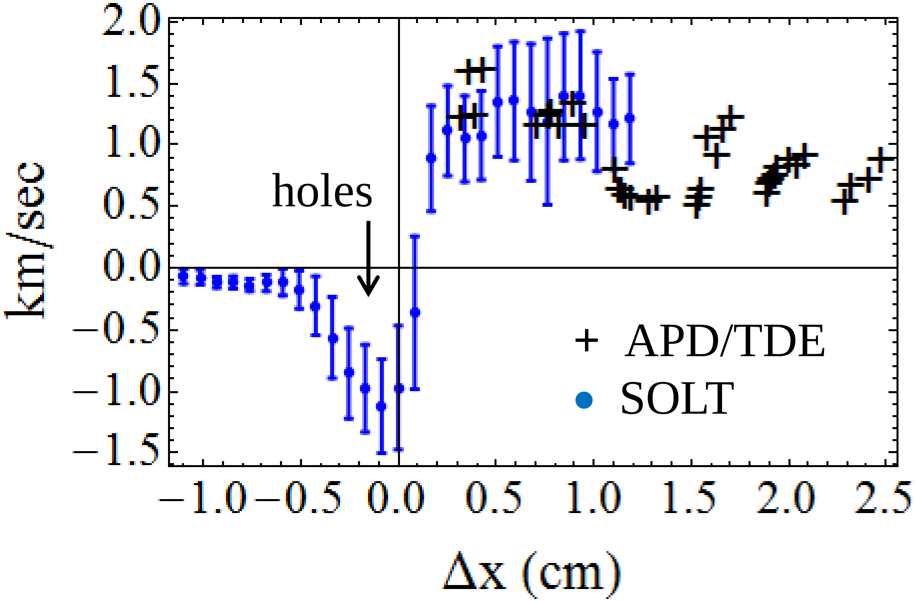
[a] quasi-linear regime [b] "big blob" regime [c] separatrix-spanning interchange mode

SOLT and measured velocities are in good agreement for the blobby case ($D_n = 0.04\ \mathrm{m^2/sec}$).

poloidal blob velocities



radial blob velocities



(+) : time-delay estimation (TDE) analysis of GPI data captured by the avalanche photo-diode (APD) array.

(□) : Fourier analysis (FA) of GPI data captured by the APD array

(O) : FA of GPI data captured by the Phantom camera (PH)

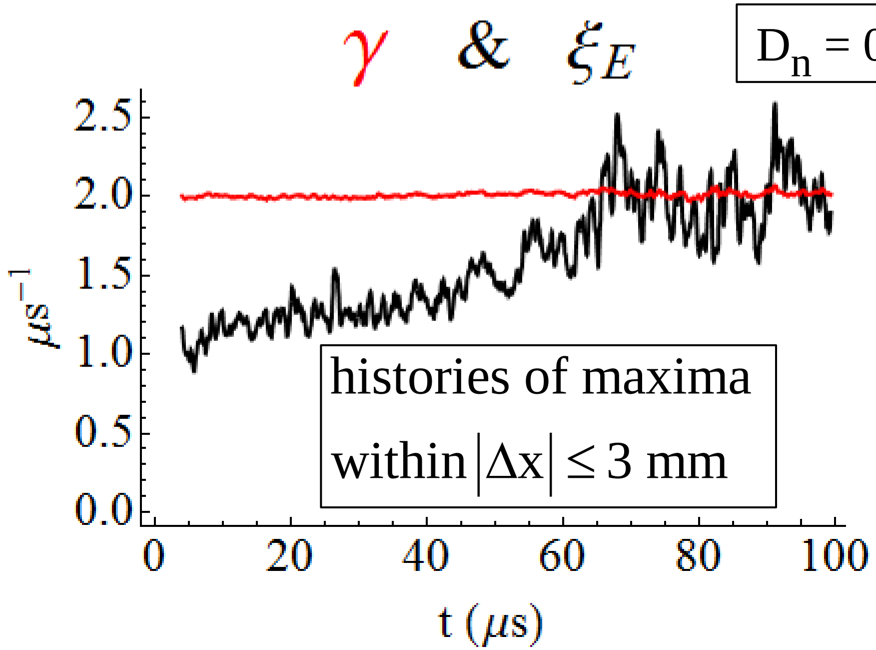
(Δ) : 2-point phase-delay analysis of fluctuations measured by the MLP

Saturation Mechanisms

1) sheared ExB flow

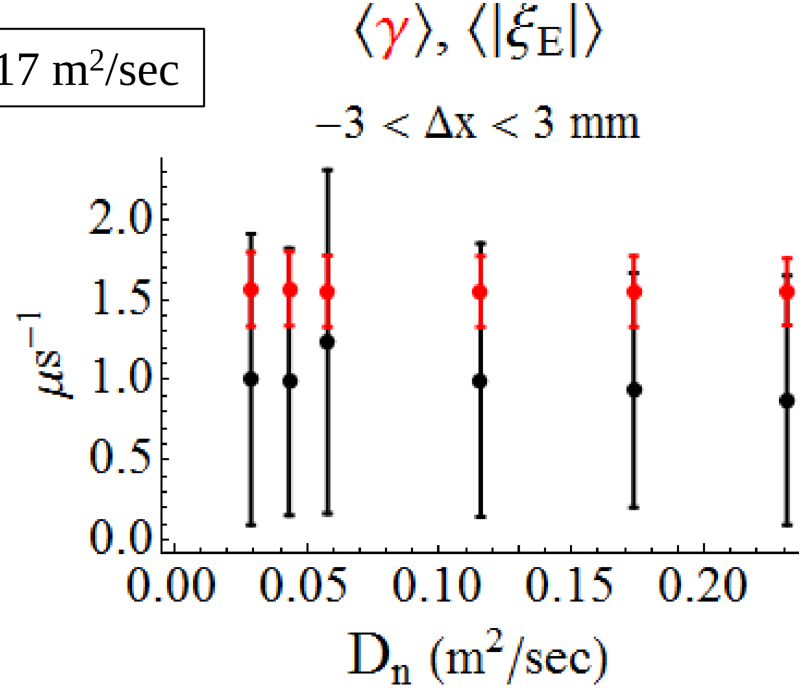
$$\xi_E = \nabla_x v_E$$

$$\gamma^2 = \frac{2}{R} \nabla_x (P_e + P_i) / m_i n$$



D_n = 0.17 m²/sec

histories of maxima within $|\Delta x| \le 3$ mm



The system saturates as the shearing rate (ξ_E) rises to meet the growth rate (γ) in a *neighborhood* of the birth zone. The mechanism acts over **radial zones**.

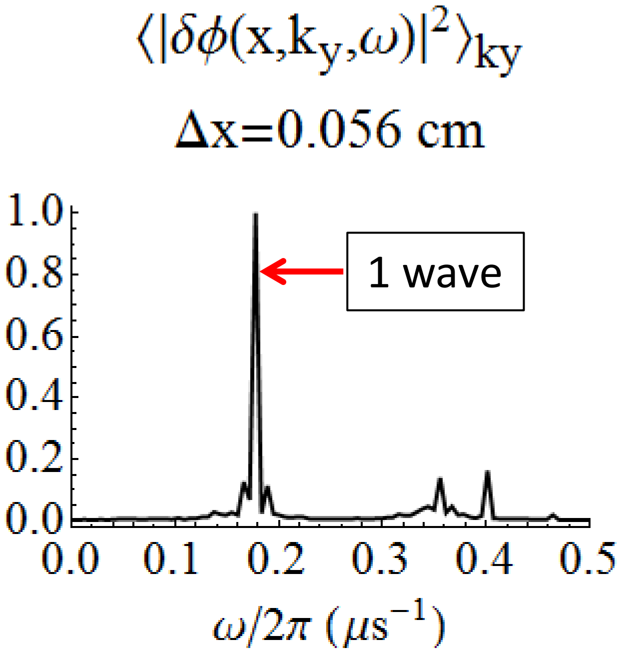
Shear-stabilization cannot be ruled out in any of the simulations, *including the weak-turbulence case*.

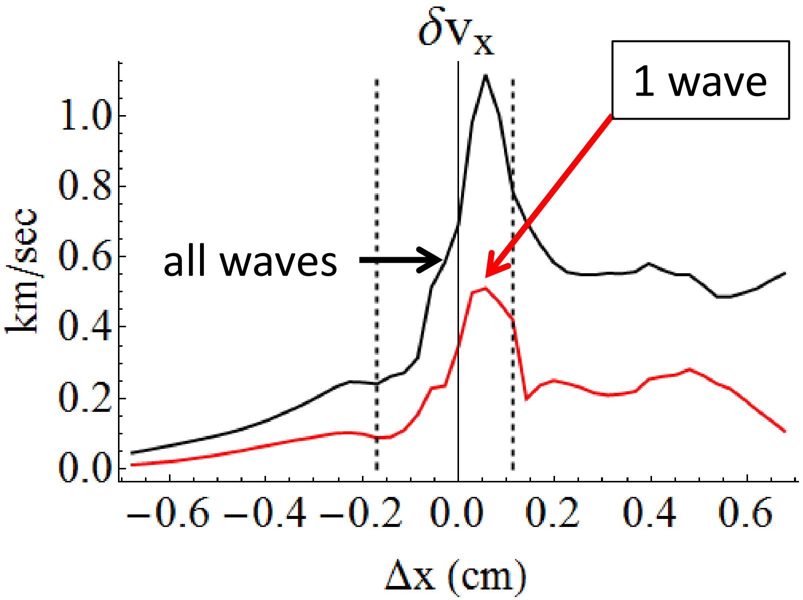
Saturation Mechanisms

2) wave breaking and profile modification

wave-breaking operates where $WB \equiv \left| \frac{\delta v_x k_x}{\omega - k_y v_E} \right| \sim 1$ profile-modification operates where $PM \equiv \left| \frac{\delta n}{\nabla_x n} k_x \right| \sim 1$

In the **weak-turbulence** case ($D_n = 0.23\ m^2/sec$) fluctuation power spectra are **dominated by a single wave** throughout the **birth zone**.



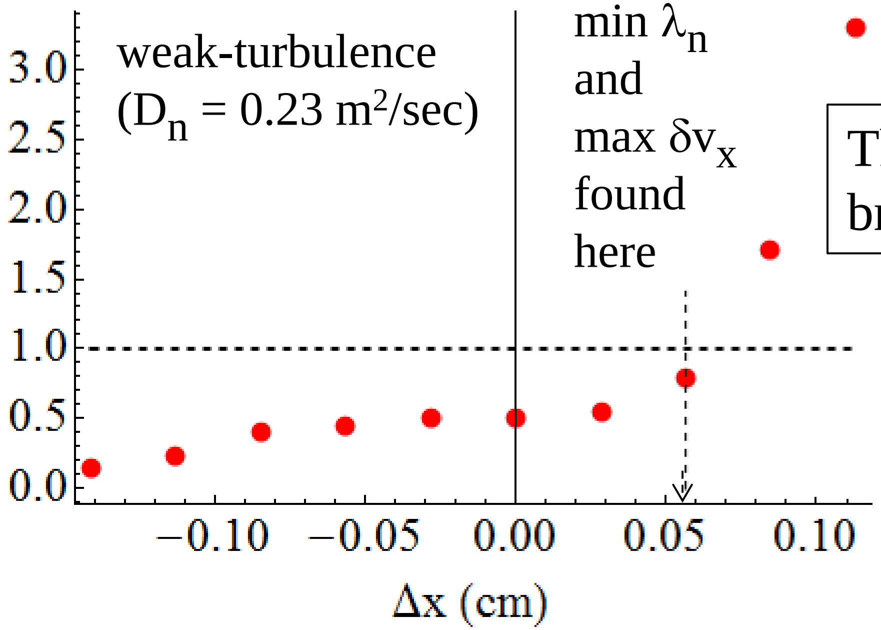


One k_y dominates the spectrum: $\omega/k_y = 0.76$ km/sec.
This is the **separatrix-spanning interchange mode** (SSI: pgs. 7, 8).

One Wave $\Rightarrow$ transparent WB and PM calculations

- (k_y, ω) : chosen to maximize $\left|\delta\phi(x,k_y,\omega)\right|^2$ at each x
- $k_x = \mathrm{Im}\left[\dfrac{\delta\phi(x,k_y,\omega)^* \, \partial_x \delta\phi(x,k_y,\omega)}{\left|\delta\phi(x,k_y,\omega)\right|^2}\right]$: phase gradient
- $\delta v_x = 2^{1/2}\left|k_y\right|\left|\delta\phi(x,k_y,\omega)\right|$

$$\mathrm{WB} \equiv \left|\frac{\delta v_x k_x}{\omega - k_y v_E}\right|$$



weak-turbulence ($D_n = 0.23\ \mathrm{m^2/sec}$)

min λ_n and max δv_x found here

The interchange mode is breaking in the near-SOL.

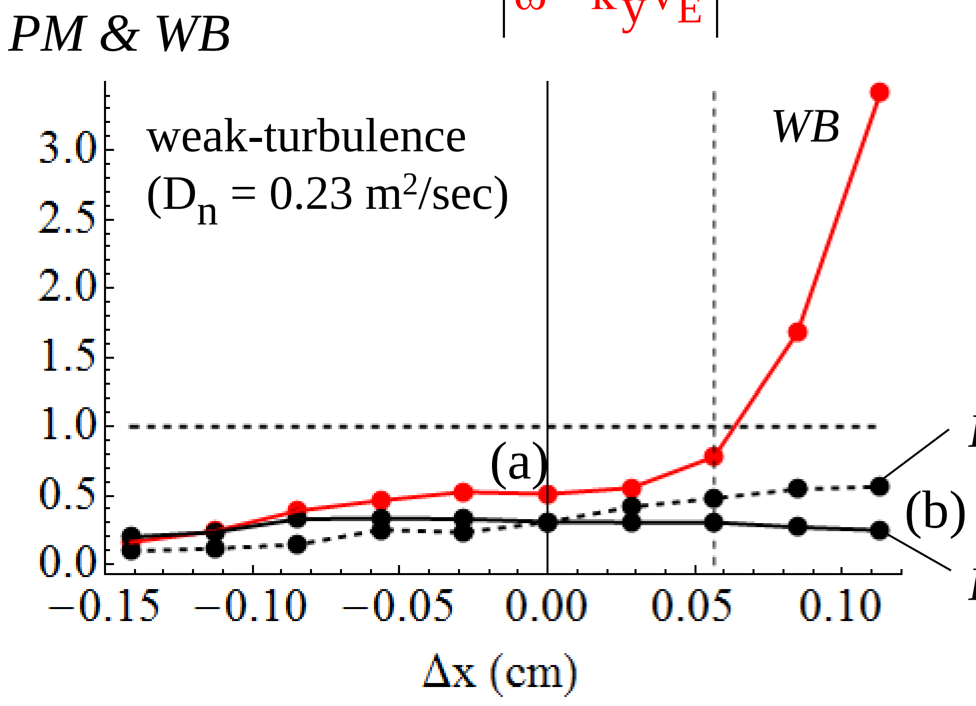
Profile Modification is Related to Wave-Breaking

$$-i(\omega - k_y \bar{v}_E)\delta n + \delta v_x \nabla_x \bar{n} + D_n (k_y^2 + k_x^2)\delta n = 0\ , \quad \bar{n} = \langle n \rangle_y$$

→ simple linear theory neglects $J_{||}$ (sheath and drift waves)

$$\Rightarrow\ PM\ \equiv \left|\frac{\delta n}{\nabla_x \bar{n}} k_x\right| = \left|\frac{\delta v_x k_x}{\omega - k_y v_E}\right| \cdot \left|\frac{\omega - k_y v_E}{i(\omega - k_y v_E) - D_n (k_y^2 + k_x^2)}\right| \equiv PM\ \ theory$$

$$\rightarrow \left|\frac{\delta v_x k_x}{\omega - k_y v_E}\right| \ (= WB)\ \ if\ \ D_n \rightarrow 0$$



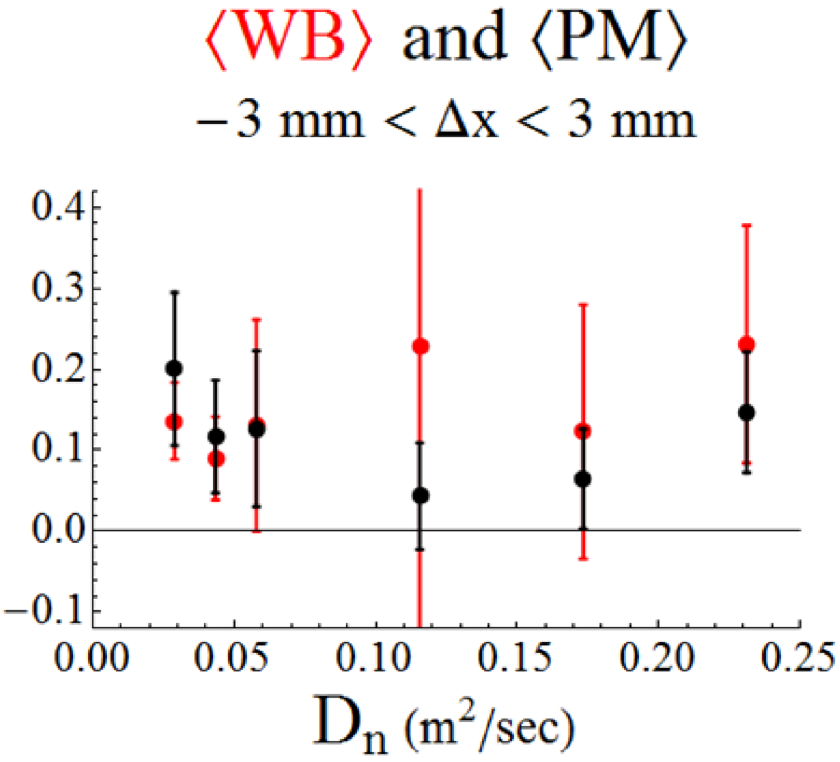
(a) At the separatrix ($J_{||} = 0$)

$D_n \neq 0 \Rightarrow PM < WB$

(b) $J_{||}$ is important for

$PM - WB$ comparison in the SOL.

Evidence for WB and PM in *all* simulations



Wave-breaking (WB, red) and profile modification (PM, black) parameters averaged over the radial interval $|\Delta x| < 3$ mm versus the density diffusion coefficient D_n. Error bars are standard deviations with respect to the average.

Summary and Conclusions

We have explored the relationship between blob velocities and mean flow velocities in the edge region of an L-mode discharge on Alcator C-Mod by conducting two-dimensional SOLT simulations.

Simulation set-up and diagnosis:

- The turbulence was driven by the plasma pressure gradient measured by TS and MLP for the discharge.
- Density fluctuation amplitudes were adjusted, by varying the density diffusion coefficient, to be consistent with those measured by MLP in the experiment.
- δn/n served as a GPI proxy.
- Blob velocities were determined from TDE analysis of the correlation function of δn.

Discharge velocity profiles were measured by 4 methods:

- TDE analysis of GPI emission recorded by avalanche photo-diode (APD)
- Fourier analysis (FA) of GPI emission recorded by APD
- FA of GPI emission recorded by a fast-framing Phantom camera
- 2-point phase-delay analysis of fluctuations measured by MLP

Summary and Conclusions (cont.)

It was found that:

- The simulations reproduced measured radial and poloidal turbulence velocities in the SOL to essentially the size of discrepancies between different diagnostics.
- The simulation blobs moved poloidally with v_E in the near-SOL.

Summary and Conclusions (cont.)

The weak-turbulence regime

- not directly relevant to the discharge – explored for perspective on the strong-turbulence regime of the discharge and for saturation mechanism clues

- **interchange mode**
  - dominates blob motion throughout the simulation domain
  - eigenfunctions localized on radial zones
  - blobs move poloidally with the mode group velocity: $v_g \sim v_E + 1/2\ v_{di}$
  - ion pressure plays a crucial role

- **saturation mechanisms**
  - **E×B flow shear stabilization:** evidence in all simulations
    - The stabilizing effect is distributed over a radial interval that includes the separatrix-spanning interchange (SSI) mode.
  - **wave-breaking and profile modification:** evidence in all simulations
    - least ambiguous in the weak-turbulence regime where a single mode (SSI) dominates the power spectra
  - **In simulations of stronger turbulence, broader power spectra challenge methodology based on a single wave.**