Reduced simulations of boundary turbulence in NSTX

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Overview

We compare a single NSTX shot to Lodestar's SOLT code turbulence simulation for the corresponding conditions.

In particular, we compare our "synthetic" version of Gas-Puff Imaging to the real thing. The potential for verifying and refining this diagnostic is underscored.

In general, we demonstrate the value of interpreting measurements of turbulent transport in the context of reduced theoretical models by making direct comparisons between experiments and relatively small-scale and efficient numerical simulations. The feasibility of making quantitative comparisons between synthetic and actual diagnostics, in the context of verification and validation, is enhanced significantly by this exercise.

Outline

Synchronize (⇒) and Compare (↔)

NSTX*		SOLT
Average Te and ne Profiles **Shot Parameters**	⇒	**Simulation Reference Profiles,** **Initial Conditions and Parameters**
GPI Data: Neutral Density Profile, Turbulent ne & Te from Experiment Atomic Emission Function from D. Stotler	⇒	**Synthetic GPI Data:** Neutral Density Profile from Experiment, Turbulent ne & Te from **Simulation** Atomic Emission Function from D. Stotler
GPI Diagnostics: Median and Average Intensity Profiles PDFs of GPI Intensity PDFs of Blob Velocity and Size by Myra et al. Correlation Lengths	↔	**Synthetic GPI Diagnostics:** Median and Average Intensity Profiles PDFs of GPI Intensity PDFs of Blob Velocity and Size by **Bloblet Analysis** Correlation Lengths
Probe (I_{SAT}) Measurements: Skewness vs. Radius, Power Spectra	↔	**Probe Measurements:** Skewness vs. Radius, Power Spectra

* Mostly shot #112825 – Analyzed in Myra et al., PoP 092509 (2006).

Equations of the SOLT model
2D : Radial (x or Δr) and Poloidal (y)

Vorticity Fluctuation

$$\partial_t \nabla^2 \tilde{\phi} = \left\{ -\mathbf{v}_E \cdot \nabla \nabla^2 \phi + \alpha_{DW} \frac{\overline{T}^{3/2}}{\overline{n}} \{\phi - T \ln(n)\} + \alpha_{sh} \sqrt{T} \left[1 - e^{\Lambda_B - \phi / T} \right] - \frac{\beta}{n} \partial_y (nT) + \hat{\mu} \nabla^4 \phi \right\}$$

Density

$$(\partial_t + \mathbf{v}_E \cdot \nabla) n = \alpha_{DW} \overline{T}^{3/2} \{\phi - T \ln(n)\} - \alpha_{sh} n \sqrt{T}\; e^{\Lambda_B - \phi / T} + S_n + D \nabla^2 n$$

Temperature

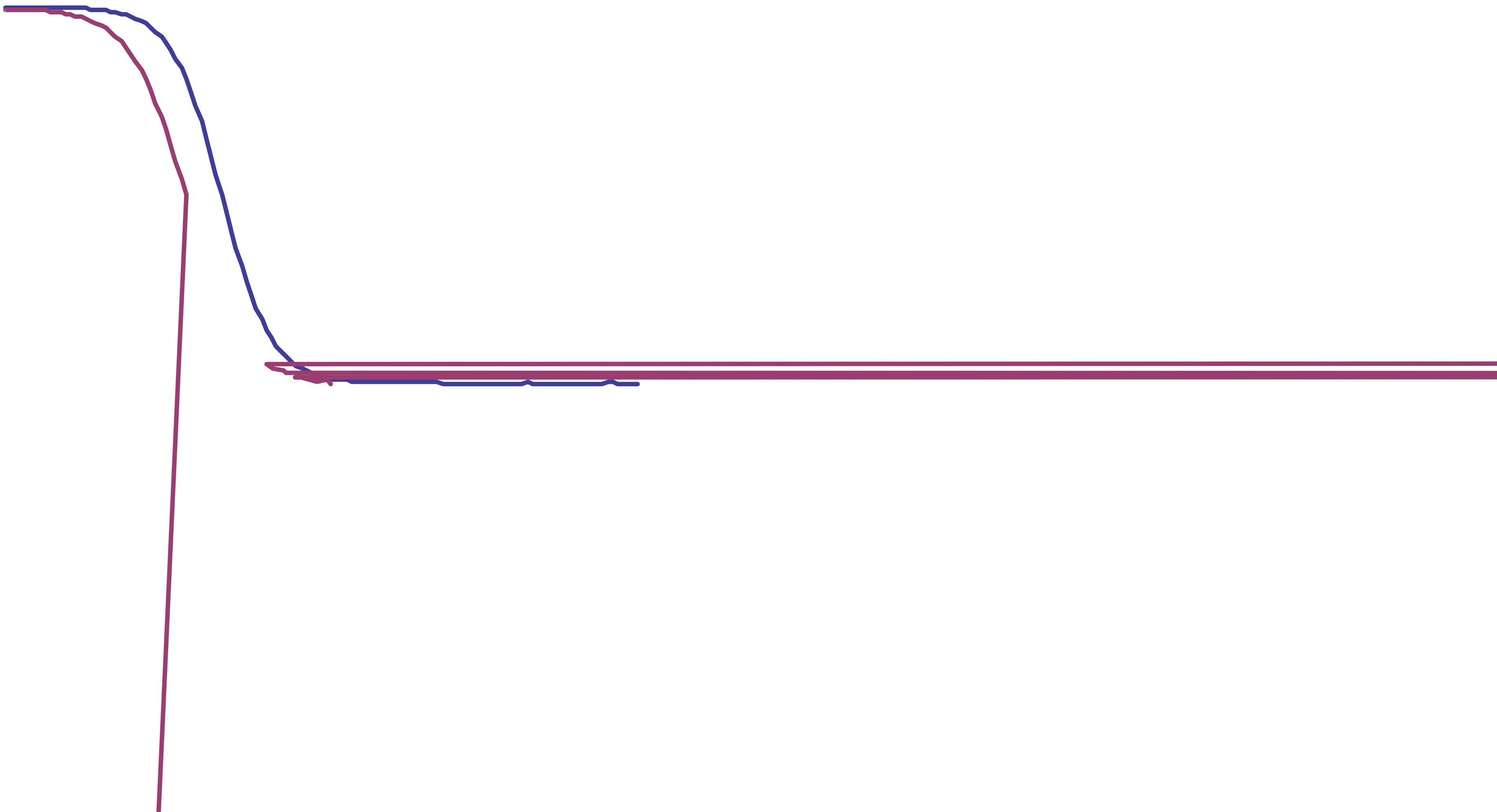
$$(\partial_t + v_E \cdot \nabla) T = -\alpha_{sh} s_E T^{3/2} e^{\Lambda_B - \varphi/T} + S_T$$

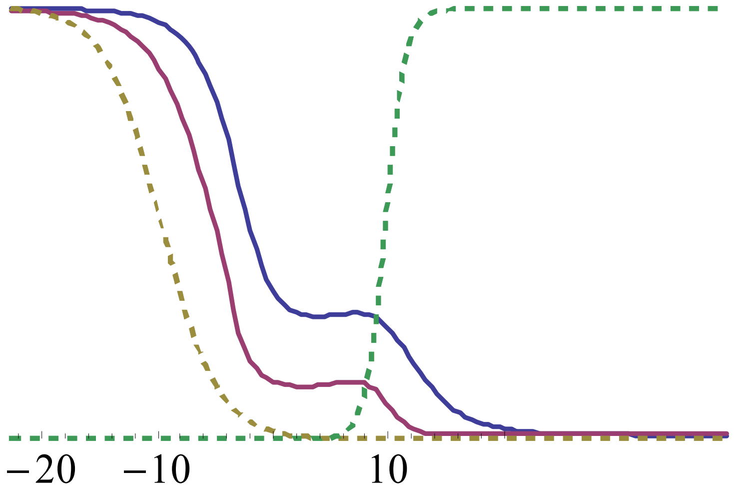
Zonal Momentum (⇒ Average Potential, $\overline{\phi}$)

$$\partial_t \left\langle n v_y \right\rangle + \partial_x \left\langle n v_x v_y \right\rangle = \int dx \left\langle \alpha_{sh} n \sqrt{T} \left[1 - e^{\Lambda_B - \phi / T} \right] \right\rangle + \overline{\mu} \partial_x^2 \left\langle v_y \right\rangle + S_\phi$$

(Here only: ⟨ ⟩ denotes a y-average. In following slides, the over-bar denotes a y-average, and ⟨ ⟩ denotes a time-average.)

- **Drift Wave and Sheath parameters, α_{DW}(x) and α_{sh}(x) model an x-dependent connection length $L_{//}$.**
- **$\beta = 2\,\rho_s / R$, the familiar curvature coefficient.**
- **$S_n = \nu_n(x)\,(n_0(x) - n)$ and $S_T = \nu_T(x)\,(T_0(x) - T)$ are sources that tend to restore the background reference profiles n_0 and T_0. ($\nu_{n,T} \sim 1$ as $x \to 0$ and are ignorably small in the SOL.)**
- **Dimensionless units based on reference choices for ρ_s, Ω_i, T_e and n_e. See below.**




−20
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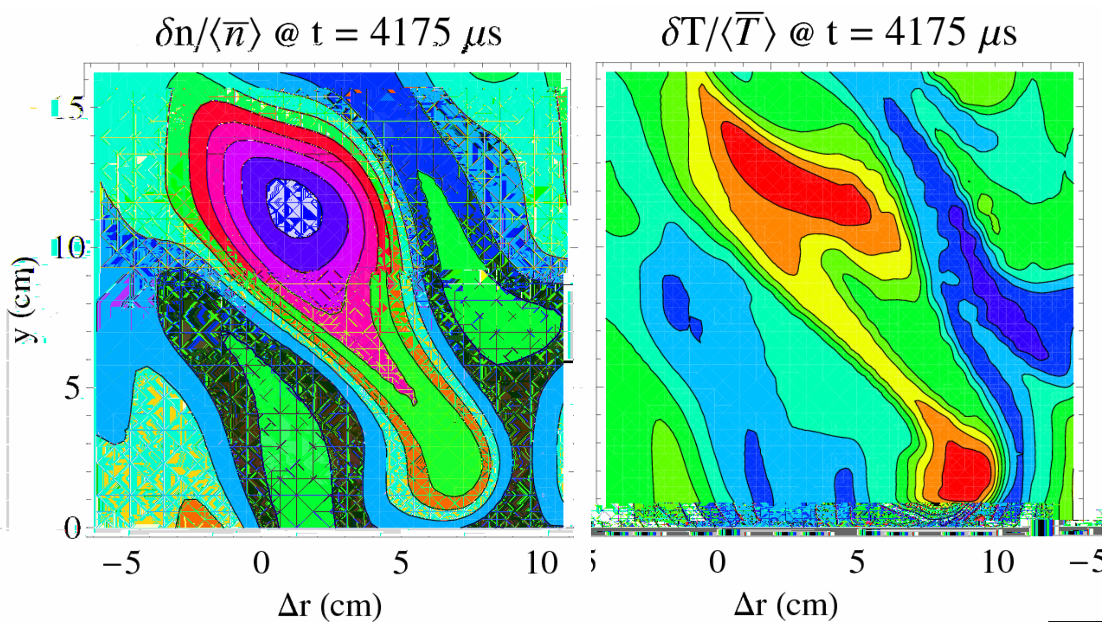
10

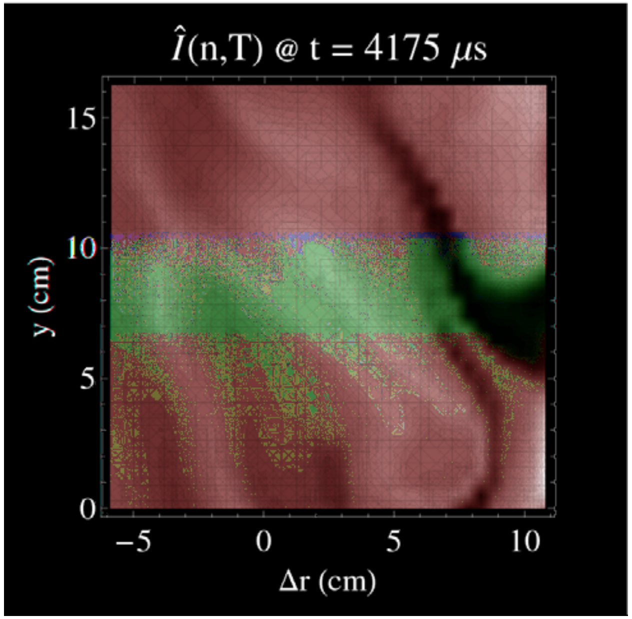
"Synthetic" GPI Intensity Patterns

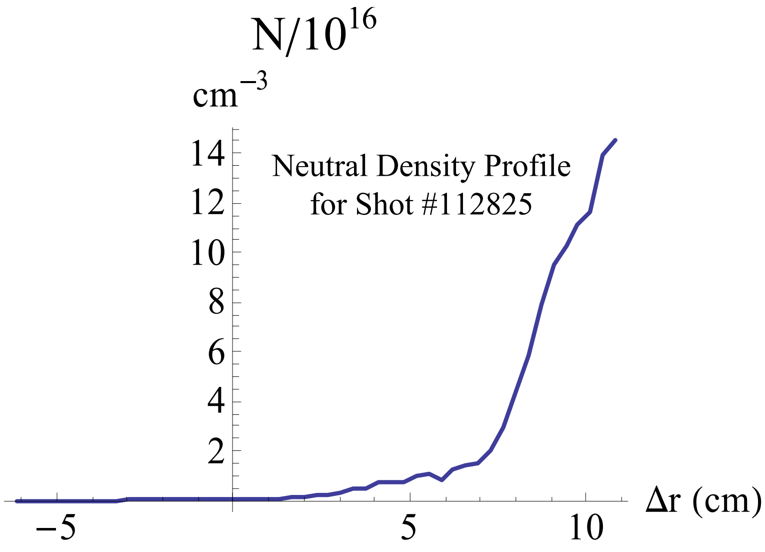
SOLT



⇒

$I \sim N\, f_{at}(n,T)$*





*$f_{at}(n,T)$: atomic emission function [D. Stotler]

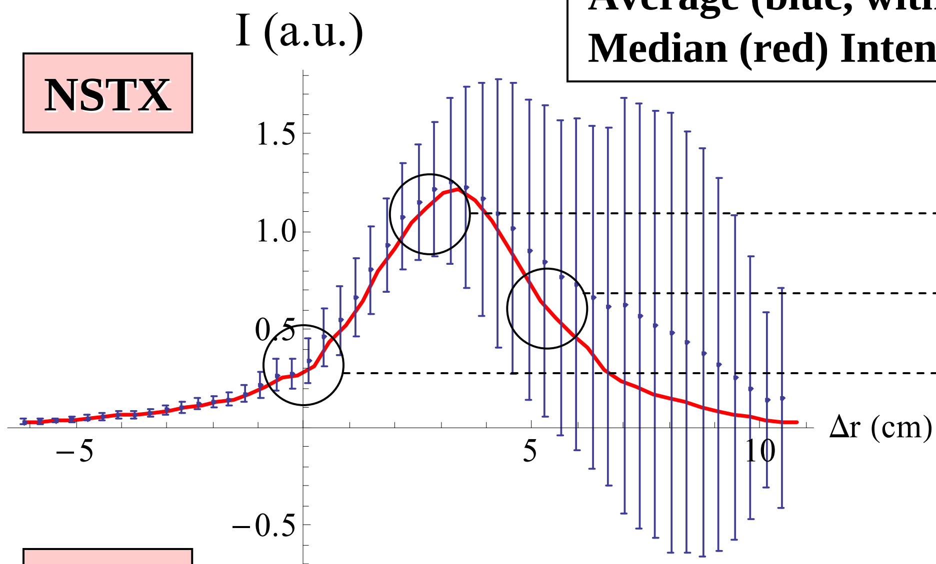
N : Neutral Density from the Shot

$\hat{I} \equiv I/\langle I \rangle$, ⟨⟩ **denotes Time Average**

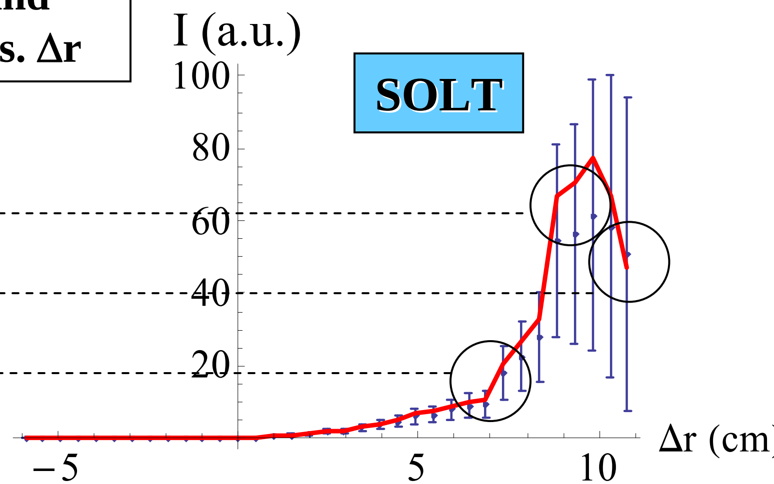
Statistics of GPI Intensity

Average (blue, with s.d.) and Median (red) Intensities vs. Δr

NSTX

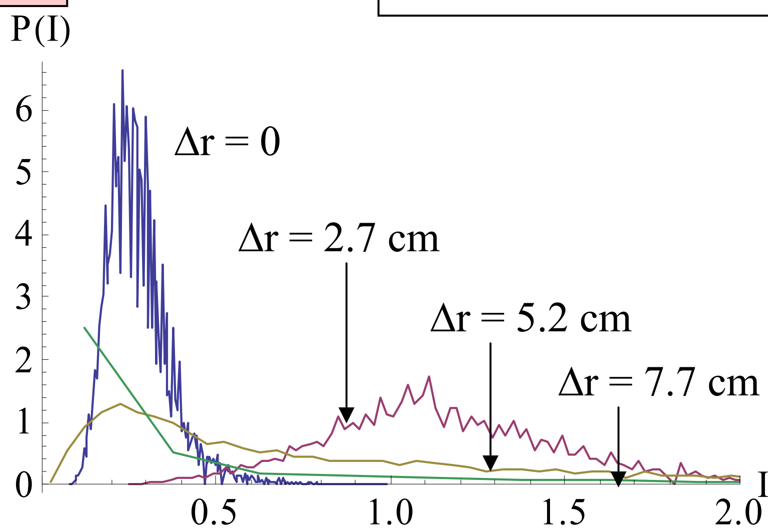


SOLT

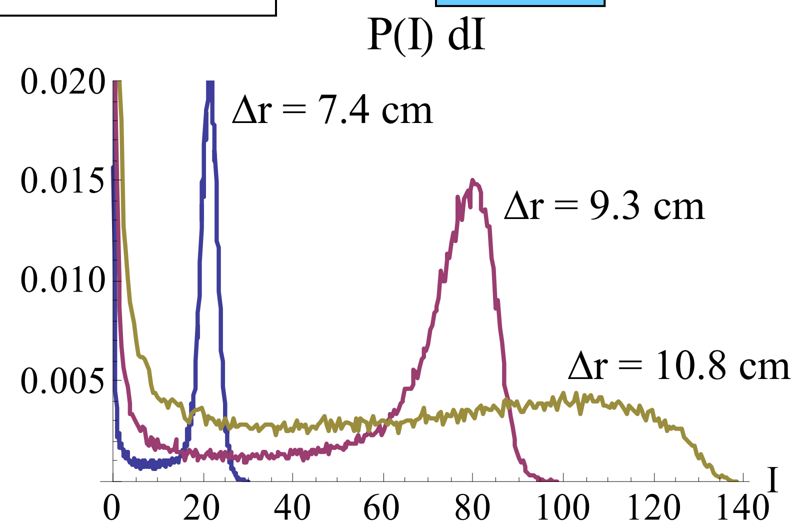


PDFs of Intensity at various Δr

NSTX



SOLT

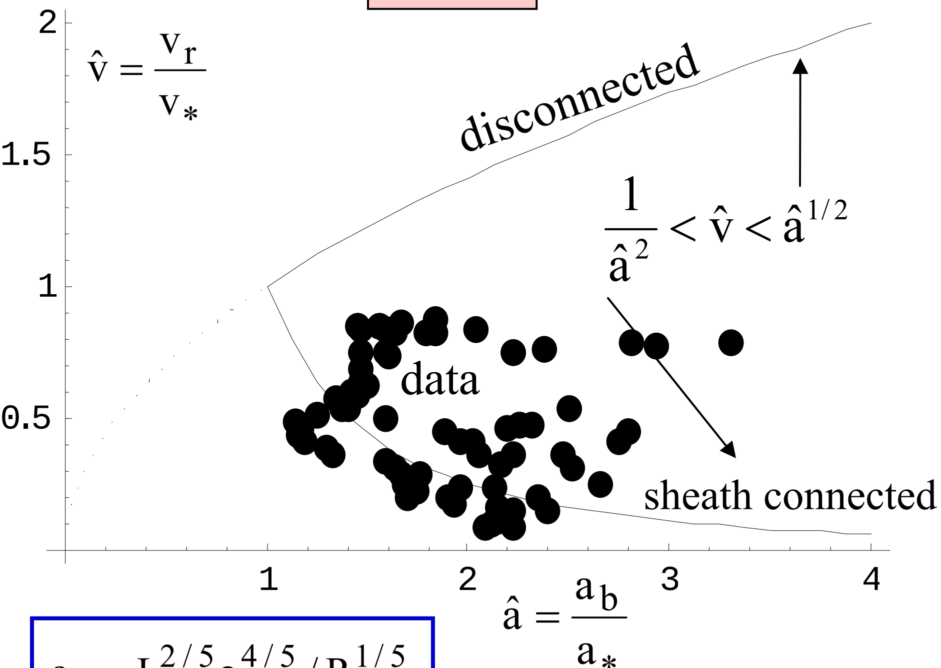


It appears that our sheath entrance is out too far. Getting this data to line up better by tuning $\alpha_{sh}(x)$ may serve to calibrate the effective connection length $L_{//}$ for this shot, in future simulations.

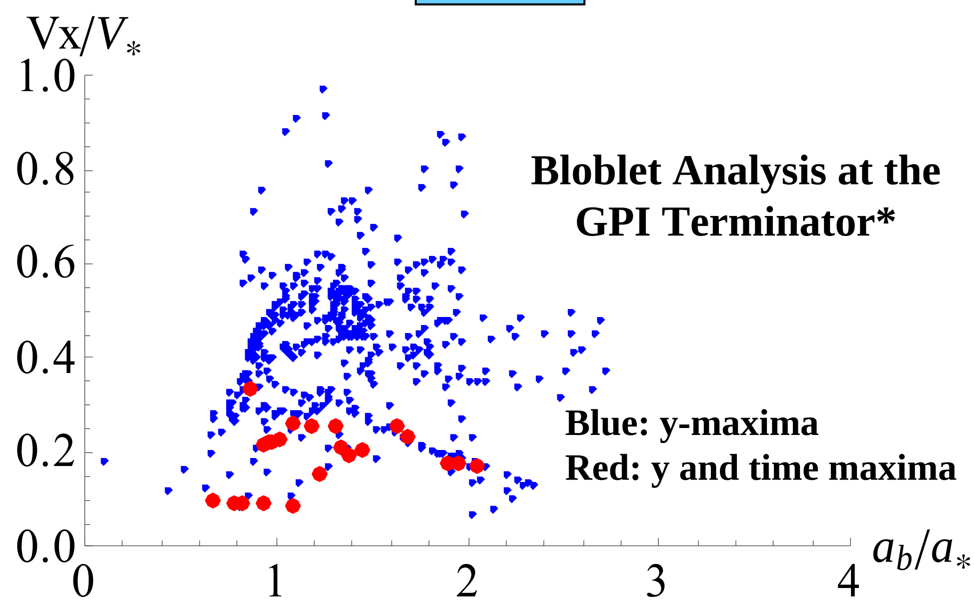
The Regime of Blob Dynamics from GPI Data

Experiment and Simulation Agree: These are sheath-connected blobs.

NSTX



SOLT



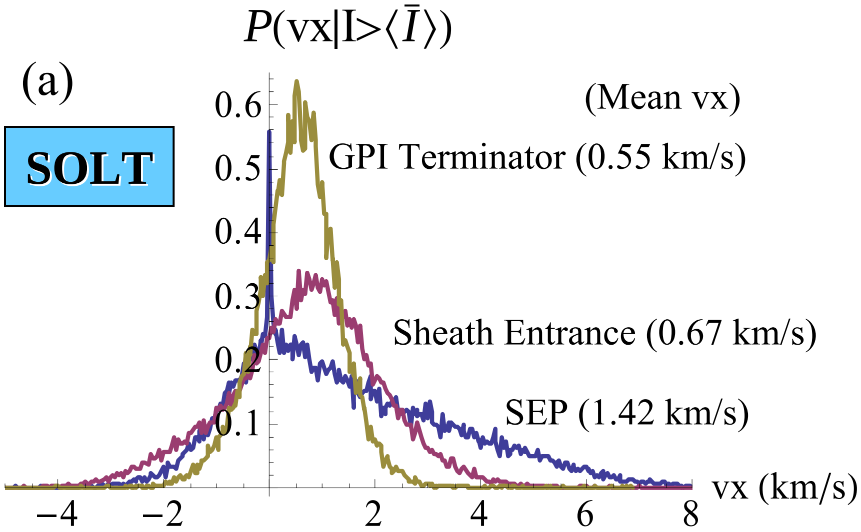
$$a_* = L_{\|}^{2/5} \rho_s^{4/5} / R^{1/5}$$

$$v_* = c_s \left(\frac{a_*}{R} \right)^{1/2}$$

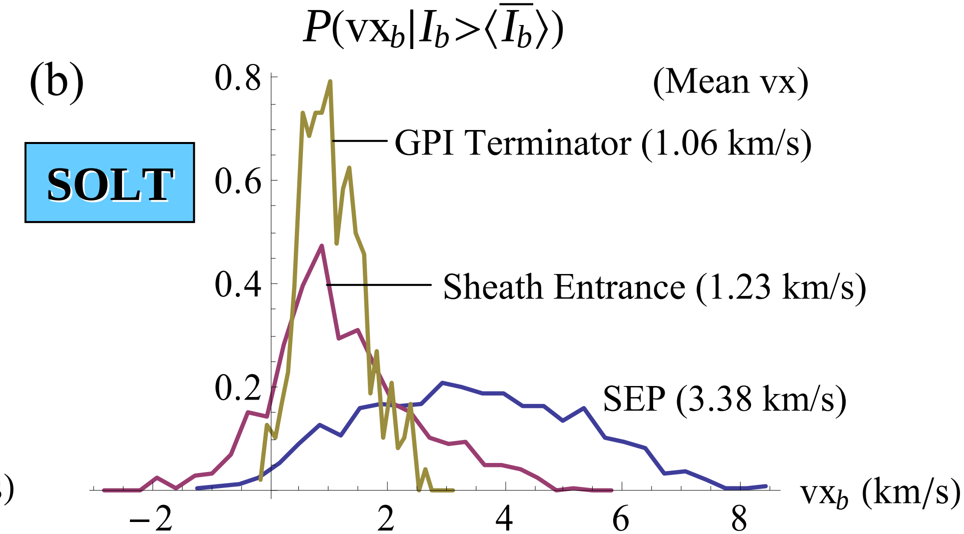
***The GPI Terminator is the greatest radial location for which we have GPI neutral density data, Δr = 10.3 cm: approximately the shadow of the rf limiter. In the simulation, the GPI terminator is 1.5 cm inside the sheath region, and the blobs are sheath-connected there.**

Statistics of GPI Intensity Blobs

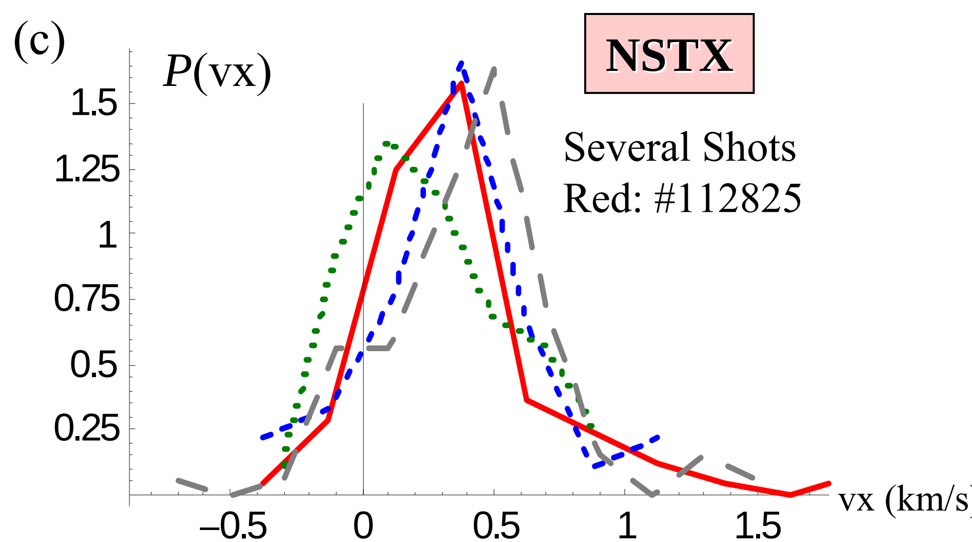
Velocities Filtered by GPI Intensity



Blob Velocities Filtered by GPI Intensity



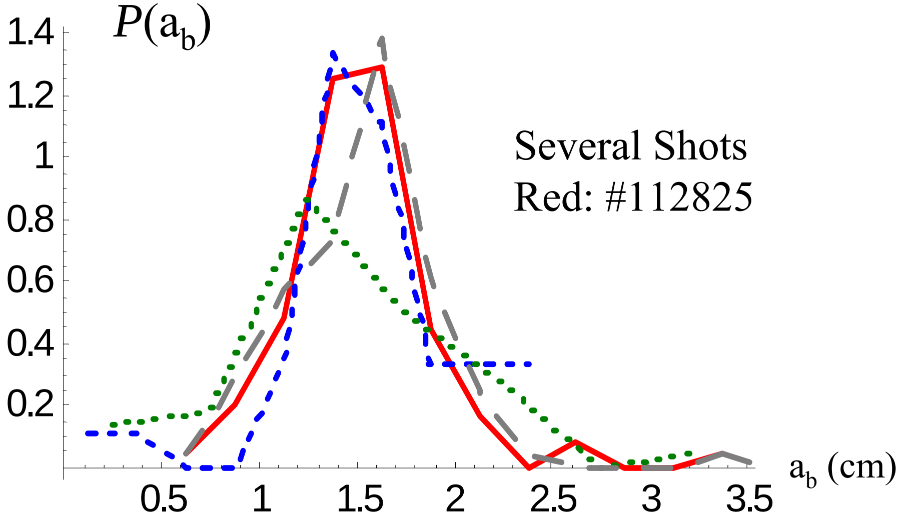
(a) Point (or *probe-like*) velocity, filtered by intensity, is skewed to positive velocity. (b) A population of blobs, identified in synthetic GPI images, accounts for these high-velocity tails. Filtered by a (local) threshold on intensity, the blob velocity distribution agrees best with that taken from NSTX shots (c) *in the sheath-connected region*. <u>This comparison is sensitive to the location of the sheath entrance in the simulation.</u>



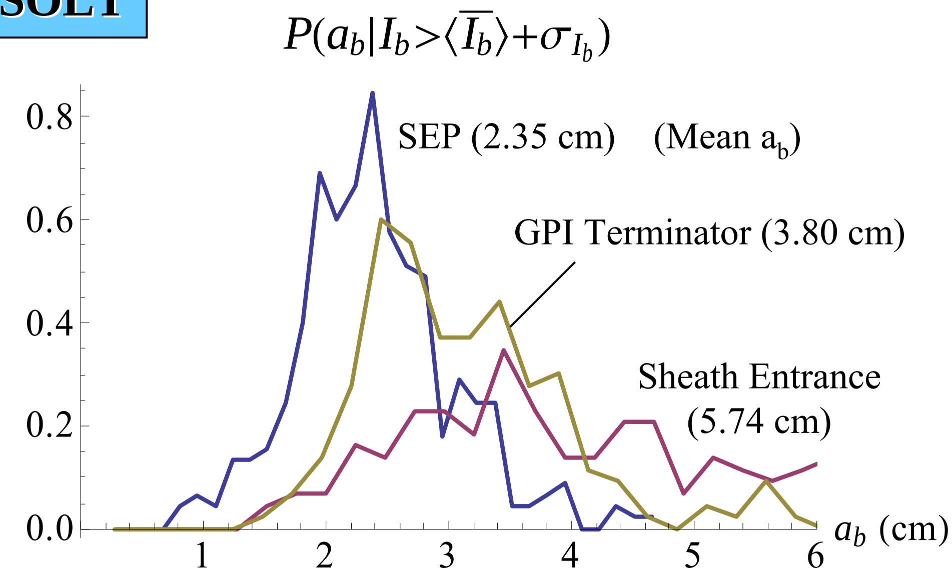
Statistics of GPI Intensity Blobs (cont.)

Size* of GPI-Intensity Blobs

NSTX



SOLT

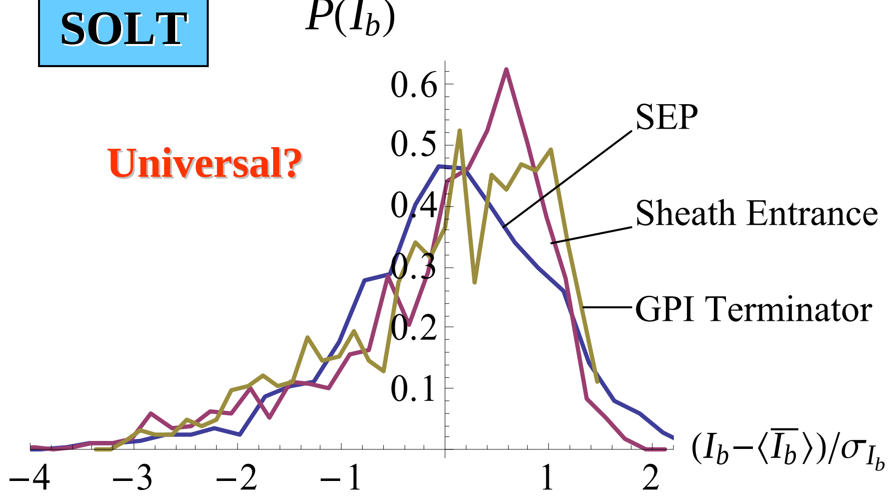


*a_b = half-width at half-max in y.

Blob sizes observed in the simulation are consistently larger than those observed in the shots. This is likely due to the stronger zonal flow shear layers in the simulation. The most persistent such layer lives at the sheath entrance where the Bohm potential turns on and the largest (most stretched-out-in-y) blobs are observed.

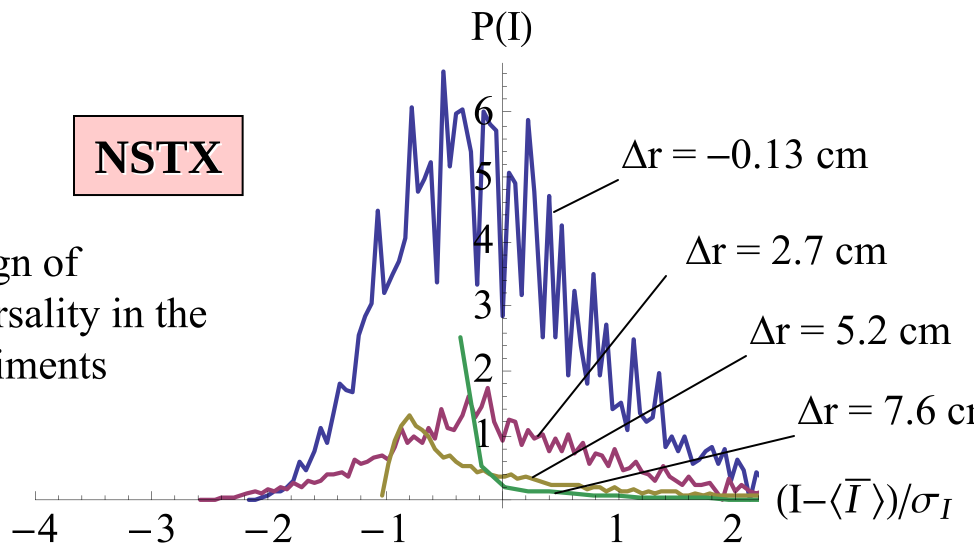
Addendum to Blob Section

SOLT



Universal?

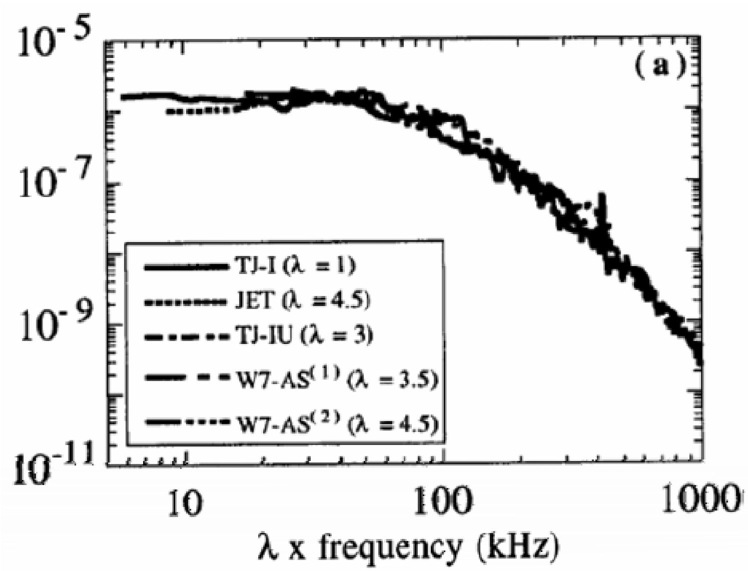
NSTX



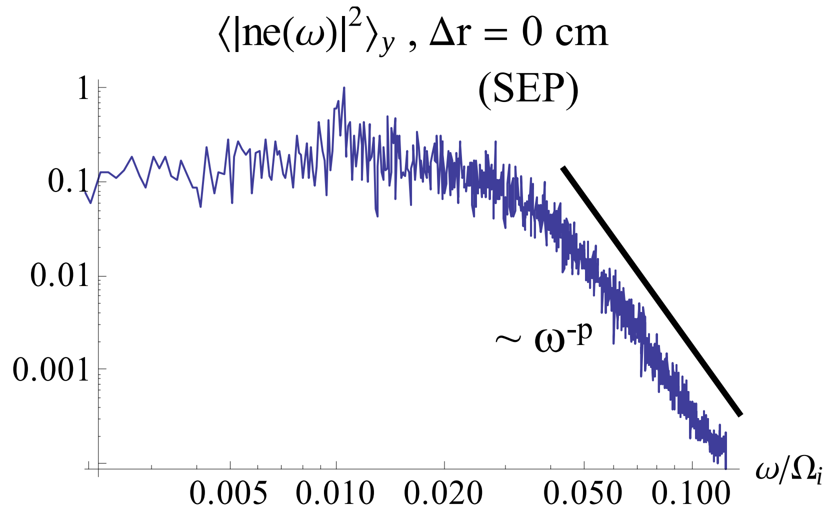
No sign of universality in the experiments

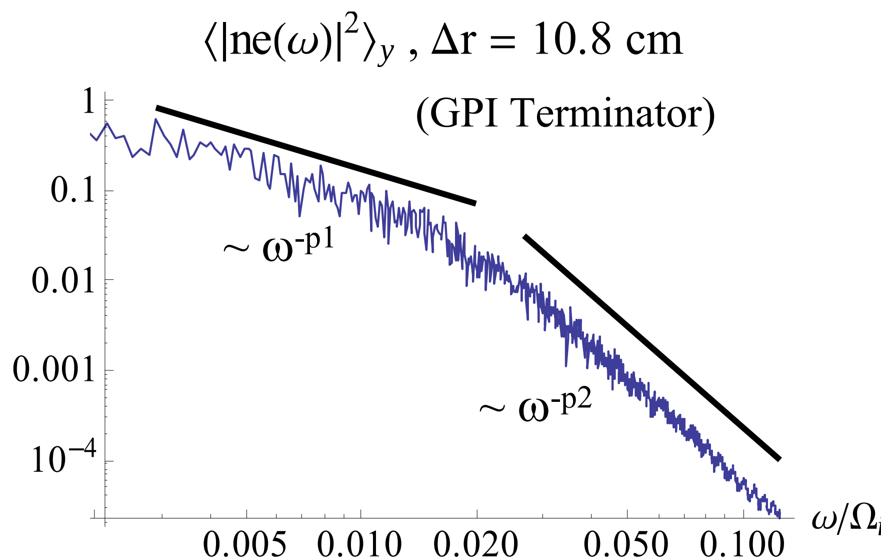
Probe Measurements: Power Spectra of Density Fluctuations

Several Experiments [Zweben 2007]



SOLT

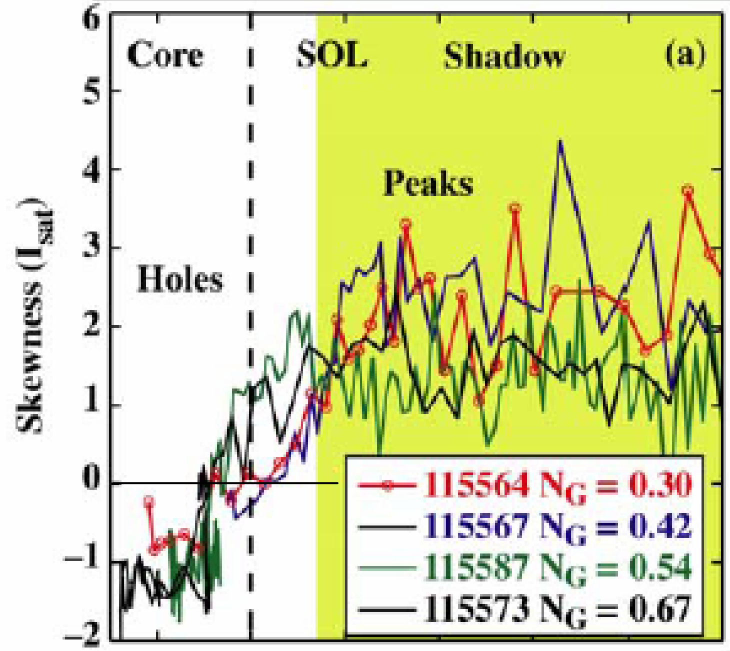




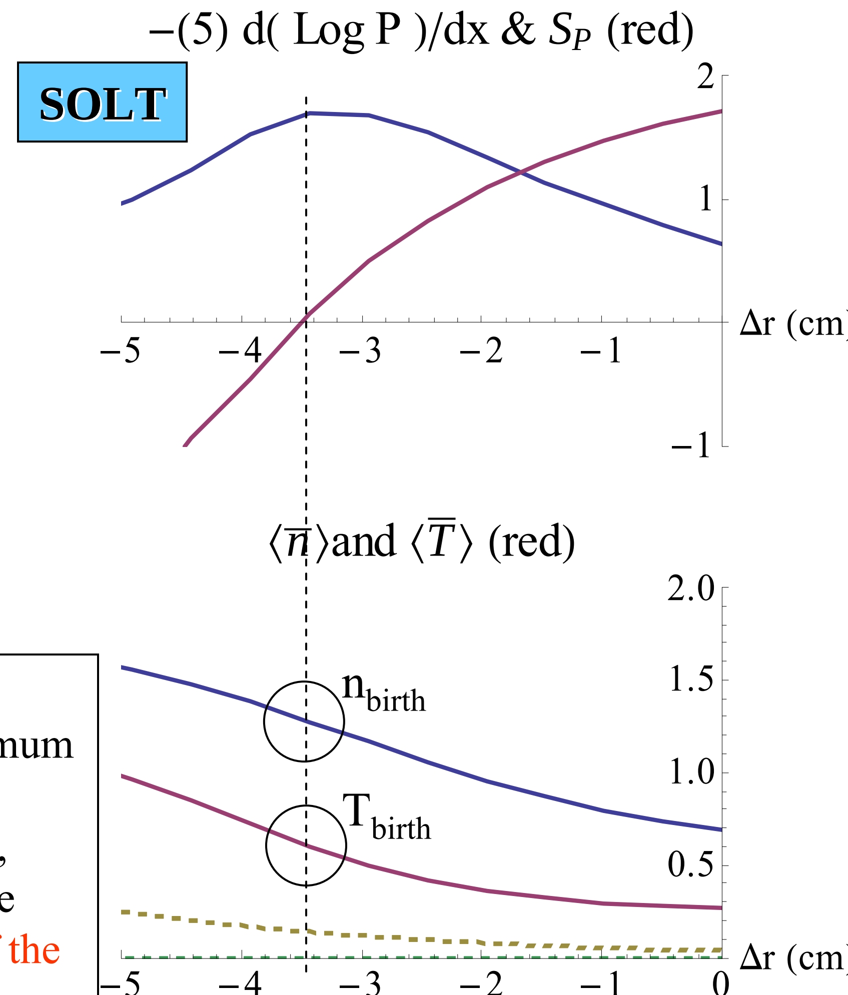
The simulation spectra demonstrate a power law behavior at high frequencies, commonly observed in many experiments. We also observe a dual power-law behavior in some spectra, particularly in the sheath-connected region. Explanation?

Probe Measurements: Skewness vs. Δr

Skewness of Saturation Current Several Shots [Boedo 2007]



Skewness of Pressure Fluctuations & Blob Birth Zone



$n_{e,birth}$ = 1.43 x 10^{13} cm^{-3}

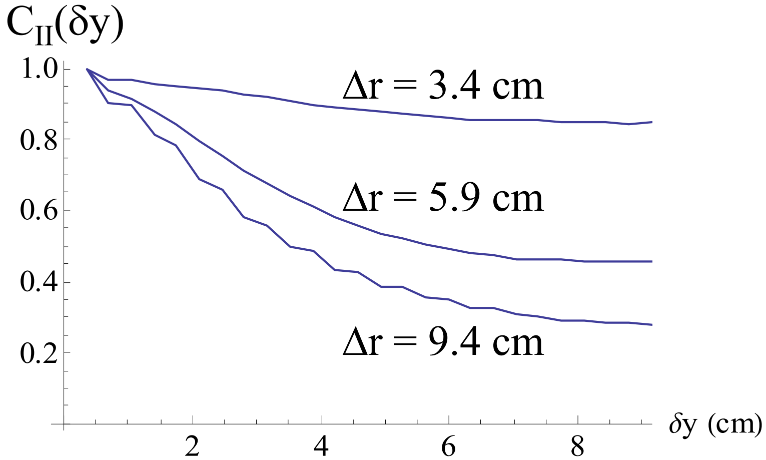
$T_{e,birth}$ = 69.8 eV

It is commonly observed that the zero of the skewness of pressure fluctuations, S_P, coincides radially with the maximum growth rate of the interchange instability, ~ −d(Log P)/dx. This region is identified as the blob birth zone. From here, blobs move out into the SOL, and holes move back into the core. The birth zone in the simulation is 6 cm to the left of the one in shot #112825 and our birth values of ne & Te are proportionately larger.

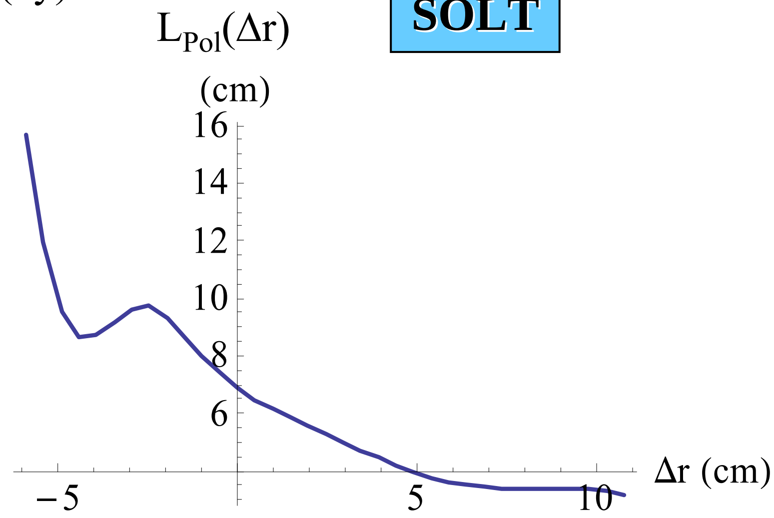
Poloidal Correlation Lengths vs. Radial Location (Δr)

Based on the Auto-Correlation function of GPI Intensity Fluctuations, $C_{II}(\delta y)$

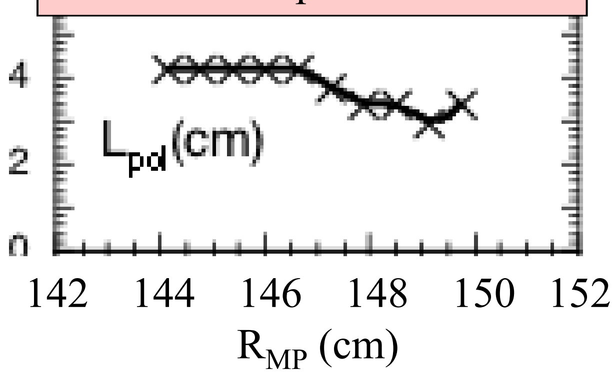
NSTX



SOLT



Poloidal Correlation Length of GPI Intensity Fluctuations from Experiment*

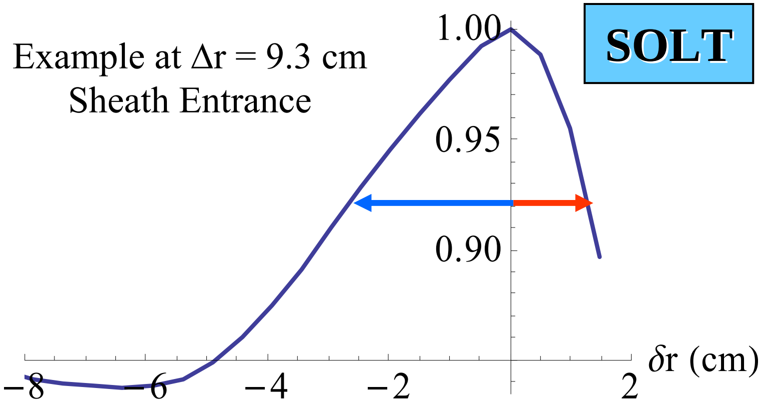


Poloidal Correlation Length decreases with increasing radius, except near the birth zone where the linear instability correlates fluctuations.

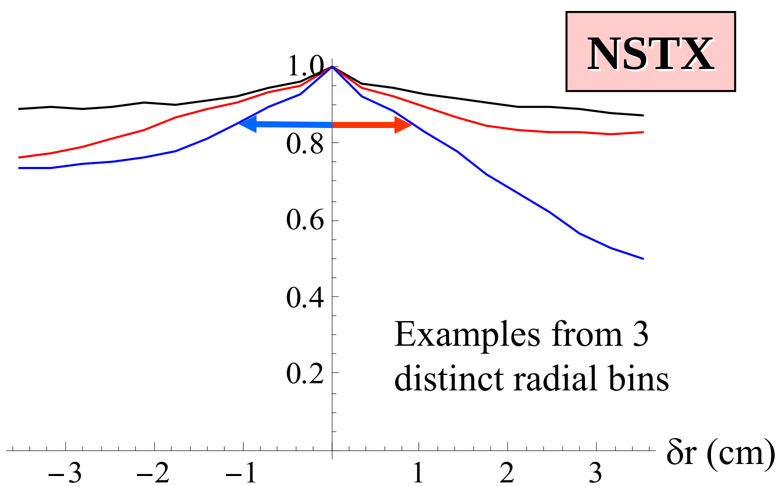
*S.J. Zweben et al., Nucl. Fusion **44**, 134 (2004).

Radial Correlation Lengths vs. Radial Location (Δr)

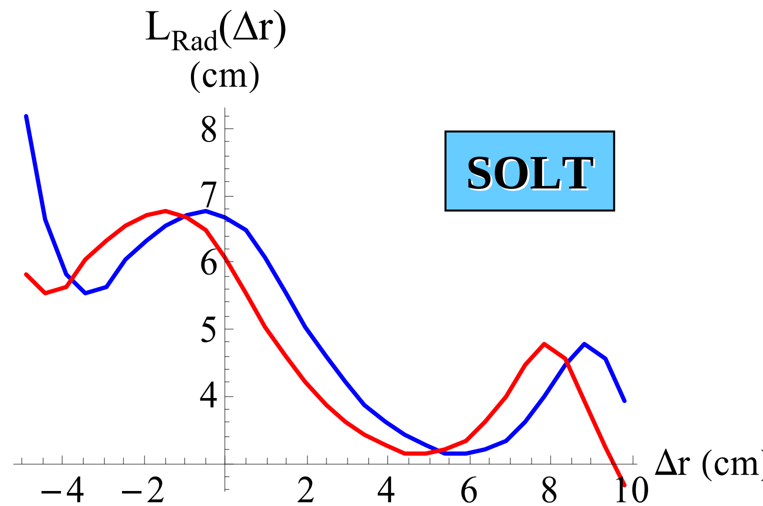
Auto-Correlation Function of GPI Intensity
$Corr_{I,I}(\delta r)$ vs. (δr)

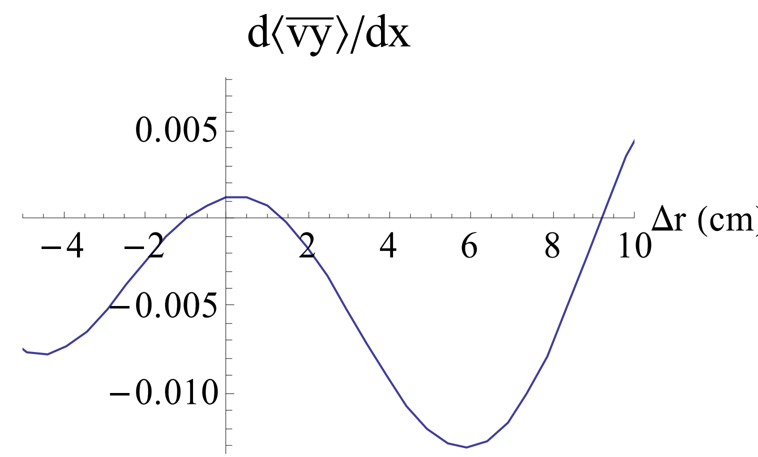


The turbulence is radially inhomogeneous;
there are clearly discernable left and right correlation lengths.
There is a strong hint of this in the experiment:*



*Though the data is a bit coarse for this analysis.





The shear rate of the zonal flow engenders radial decorrelation, as often observed.

Summary

Points of **Agreement** between simulation and experiment:

- Qualitative features of GPI Intensity Patterns (Blobs)
- Blob dynamics, e.g., PDFs of Blob Velocity,
  in the Sheath-Connected Region
- Power Spectra of Density Fluctuations – Power Laws Observed
- Probe measurements – Skewness and Correlation Lengths
  in qualitative agreement

Points of **Disagreement**:

- Turbulent ne and Te Profiles / Birth Zone Locations
- Mean GPI Intensity Profiles vs. Δr
- PDFs of Blob Size
  - all likely due to differences in parallel connection length
  profiles, $\alpha_{sh}(x)$, and the resulting differences in Zonal Flows

Conclusion

Our first shot at the reduced (SOLT) modeling of NSTX experiments, with synthetic GPI diagnostics in place, have met with encouraging success. But *one simulation* is hardly sufficient evidence by which to judge the promise of this potentially powerful diagnostic of edge and SOL turbulence. This presentation demonstrates a capability and not (yet) predictability.