Comparison of Edge Turbulence Imaging at Two Different Poloidal Locations in the Scrape-off Layer of Alcator C-Mod

S.J. Zweben[1], J.L. Terry[2], M. Agostini[3], W.M. Davis[1], A. Diallo[1], R.A. Ellis[1], T. Golfinopoulos[2], O. Grulke[4], J.W. Hughes[2], B. LaBombard[2], M. Landreman[2], J.R. Myra[5], D.C. Pace[6], D.P. Stotler[1]

[1] Princeton Plasma Physics Laboratory, Princeton, NJ 08540 USA
[2] Massachusetts Institute of Technology, Cambridge, MA 02139 USA
[3]Consorzio RFX, Associazione EURATOM, I-35127, Padova, Italy
[4] Max Planck Institute for Plasma Physics, EURATOM Association, D-17491 Greifswald, Germany
[5] Lodestar Research Corporation, 2400 Central Ave., Boulder CO 80301, USA
[6] General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA

Poster – Transport Task Force Meeting, Santa Rosa, CA
April 2013

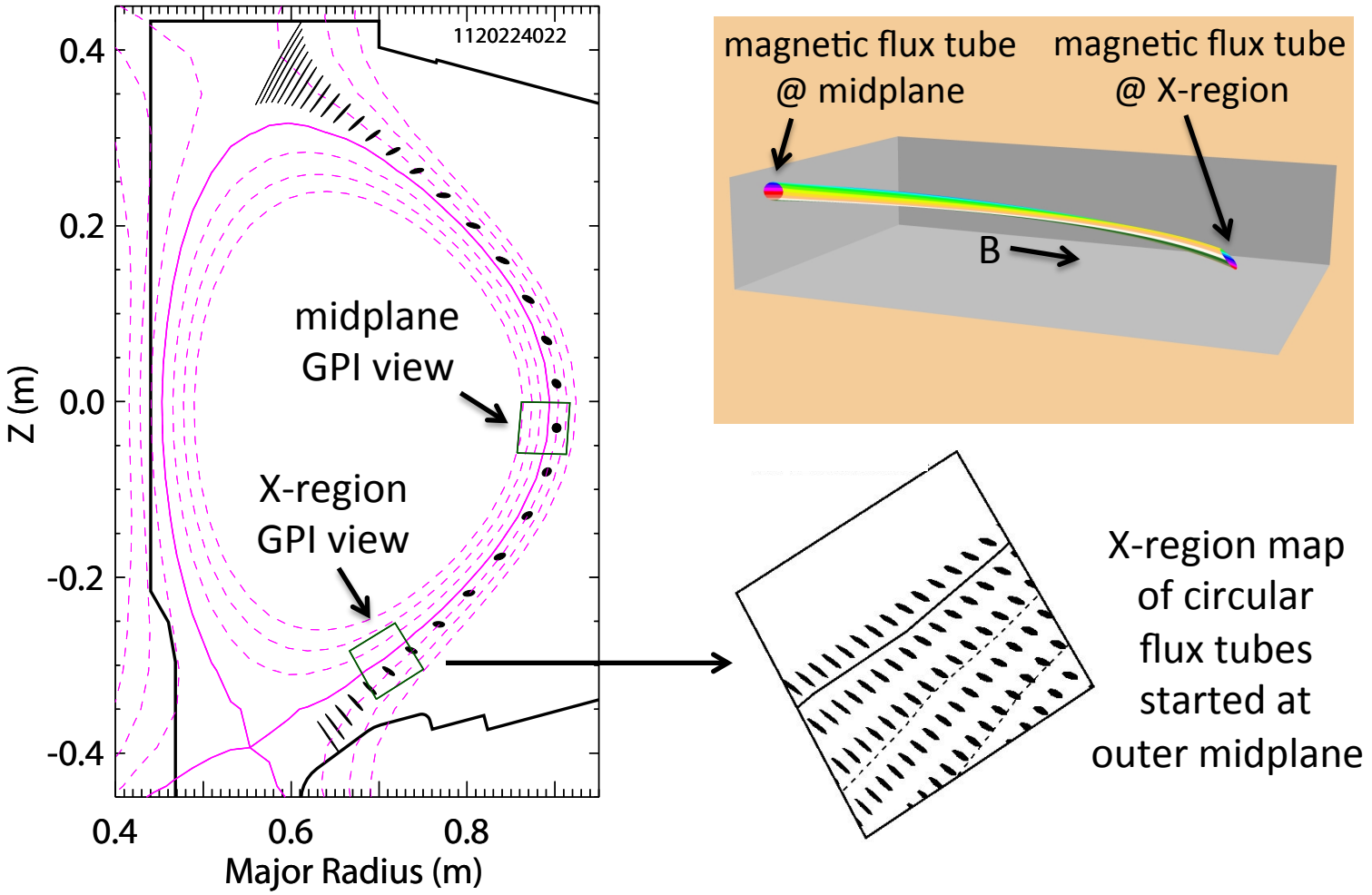
Motivating Questions (and Results)

- Is the *turbulence structure* in the SOL the same near the outer midplane and the lower X-point region of C-Mod ?
  - relative fluctuation levels and frequencies are similar
  - size and ellipticity of turbulence cross-correlation are similar
  - tilt angle of turbulence correlations are significantly different

- Is the *turbulence velocity* in the SOL the same near the outer midplane and the lower X-point region of C-Mod ?
  - time-averaged turbulence velocities are usually different
  - fluctuations in turbulence velocity are usually different

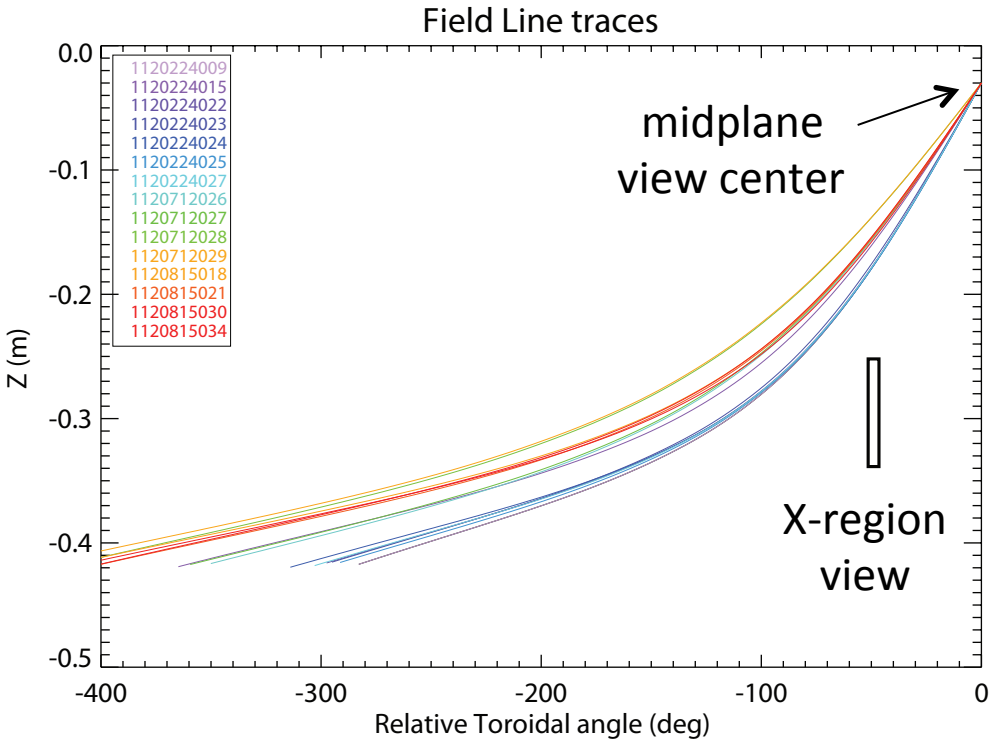
Location of Two Gas Puff Imaging Views

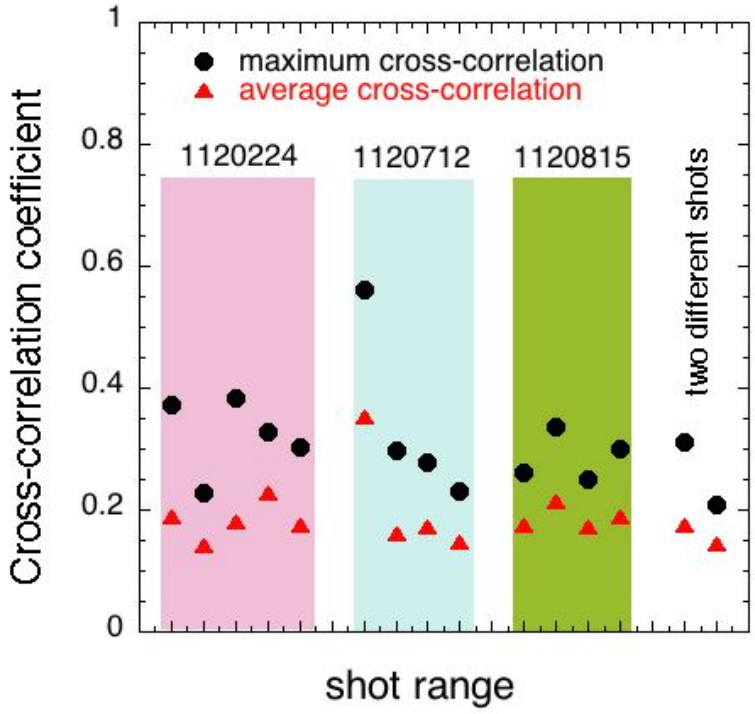
showing field line map of circular flux tube started at outer midplane



B Field Line Mapping Between Views

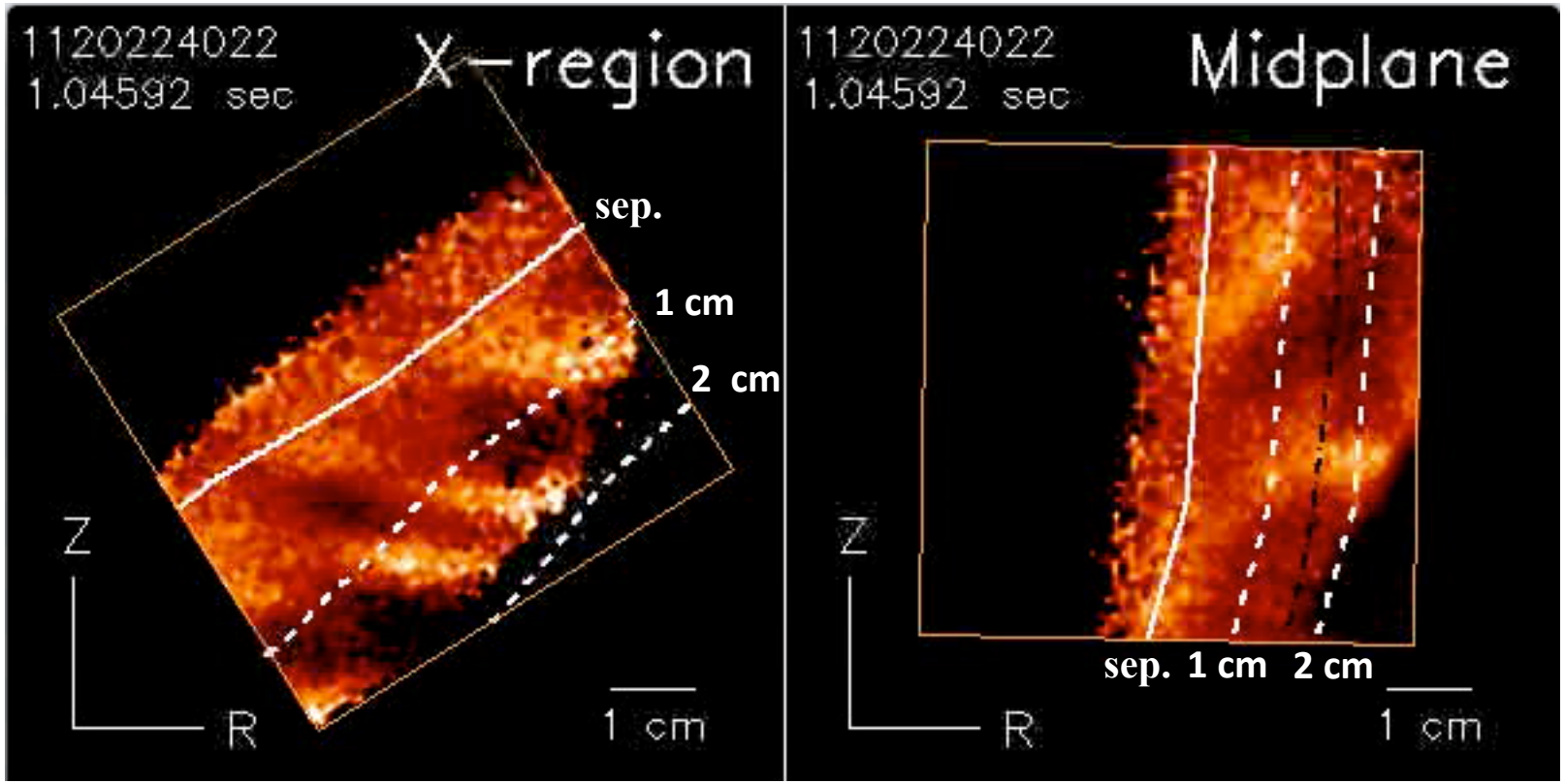
- B field lines do *not* connect between midplane and X-region views
- Cross-correlation of turbulence between these two views is low





Typical Images of Edge/SOL Turbulence

- Made using HeI (587.6 nm) line filter looking at He gas puffs
- Camera @ 391,000 frames/sec, 2 μs/frame, 64x64 pixels/frame
- Normalized movies can be seen http://w3.pppl.gov/~szweben



Time-Averaged Turbulence Analysis

- Subsequent analyses averaged over 3-5 msec in steady-state
- Obvious transients avoided (i.e. no ELMs or L-H transitions)
- Typical SOL parameters from edge Thomson scattering below

parameter	**1120224**	**1120815**
regime	L-mode	H-mode
ρ (cm)	0.5±0.5	0.5±0.5
n_e (10^{19} m^{-3})	3.1±1.1	4.9±0.6
T_e (eV)	21±5	18±2
L_n (cm)	1.1	1.2
L_{Te} (cm)	0.6	0.5
$L_{\|\|, min}$ (m)	~ 4	~ 8
ρ_s (cm)	~10^{-2}	~10^{-2}
$\nu_{e*}(m_e/m_i)^{1/2}$	0.4	1.6
β	~$3x10^{-5}$	~$3x10^{-5}$

Database of C-Mod Shots

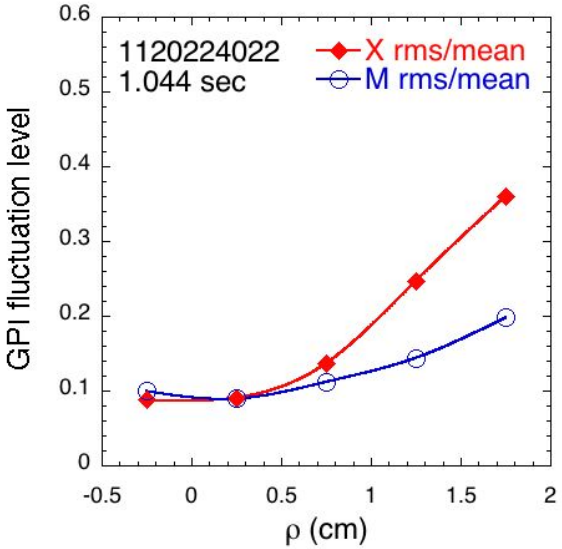
Shot	Time (sec)	I(MA)		B(T)	n (m^{-3})	RF(MW)	Gap*(cm)	Discharge type
Run day 1:								
1120224009	0.701-0.716	0.9	4.6	$1.1x10^{20}$		2.3	1.3	L-mode
1120224015	0.810-0.814	1.0	6.0	$1.3x10^{20}$		3.7	1.1	L-mode
1120224022	1.044-1.048	1.0	5.2	$1.0x10^{20}$		2.6	1.2	L-mode
1120224023	1.113-1.116	1.0	5.2	$1.4x10^{20}$		3.0	1.3	ELM-free H-mode
1120224024	1.130-1.135	1.0	5.2	$1.7x10^{20}$		2.8	1.5	ELM-free H-mode
1120224027	1.144-1.148	0.9	4.6	$1.3x10^{20}$		3.0	1.4	L-mode
Run day 2:								
1120712026	1.440-1.444	0.73	4.2	$3.5x10^{20}$		0	0.2	Ohmic H-mode
1120712027	1.440-1.444	0.73	4.2	$3.6x10^{20}$		0	0.1	Ohmic H-mode
1120712028	1.440-1.443	0.73	5.0	$2.6x10^{20}$		0	0.1	Ohmic H-mode
1120712029	1.440-1.443	0.73	5.0	$2.2x10^{20}$		0	0.1	Ohmic H-mode
Run day 3:								
1120815018	1.270-1.274	0.90	5.6	$2.5\ x10^{20}$		2.9	1.4	ELMy H-mode
1120815021	1.190-1.193	0.91	5.6	$2.0\ x10^{20}$		2.0	1.4	ELMy H-mode
1120815030	1.260-1.264	0.91	5.6	$1.9\ x10^{20}$		2.6	1.5	ELMy H-mode
1120815034	1.150-1.153	0.91	5.6	$2.0\ x10^{20}$		3.1	1.7	ELMy H-mode

- outer gap distance between outer midplane separatrix and innermost outer limiter

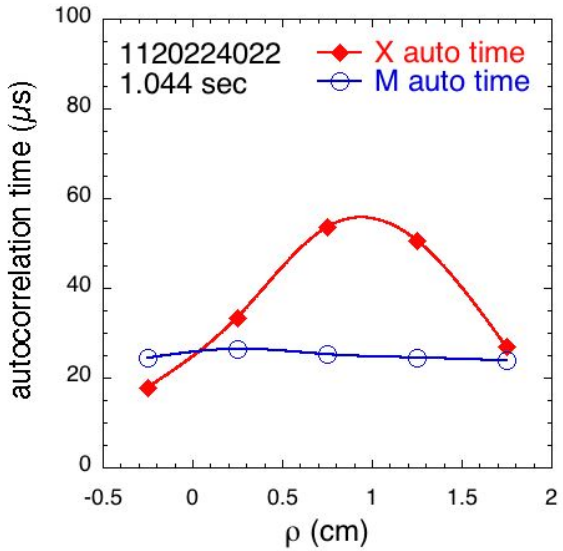
Basic Turbulence Characteristics

- Relative fluctuation level similar at midplane and X-region
- Autocorrelation time similar (sometimes larger in X-region)
- Frequency spectrum similar in midplane and X-region

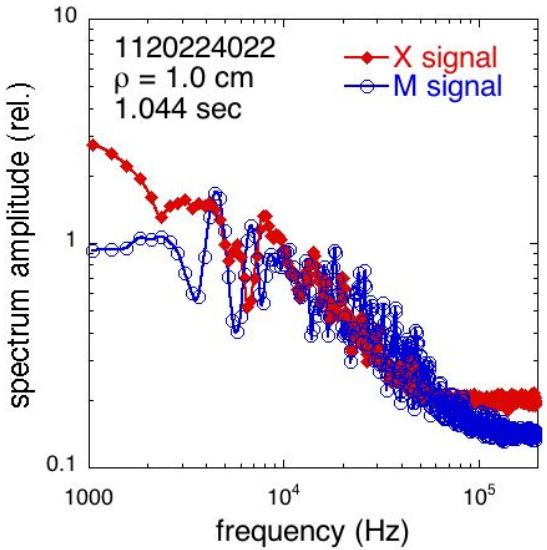
RMS/mean vs. radius



autocorrelation time

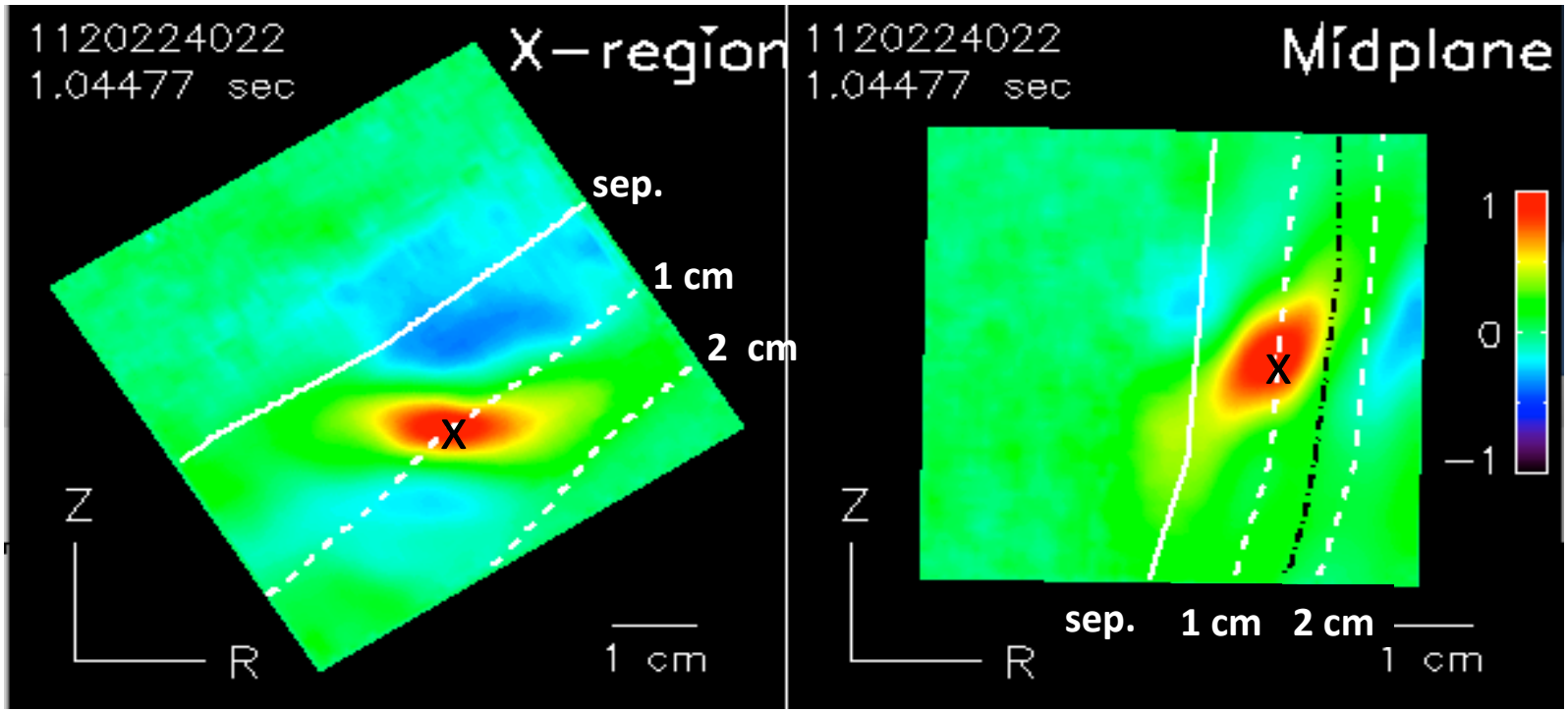


frequency spectrum



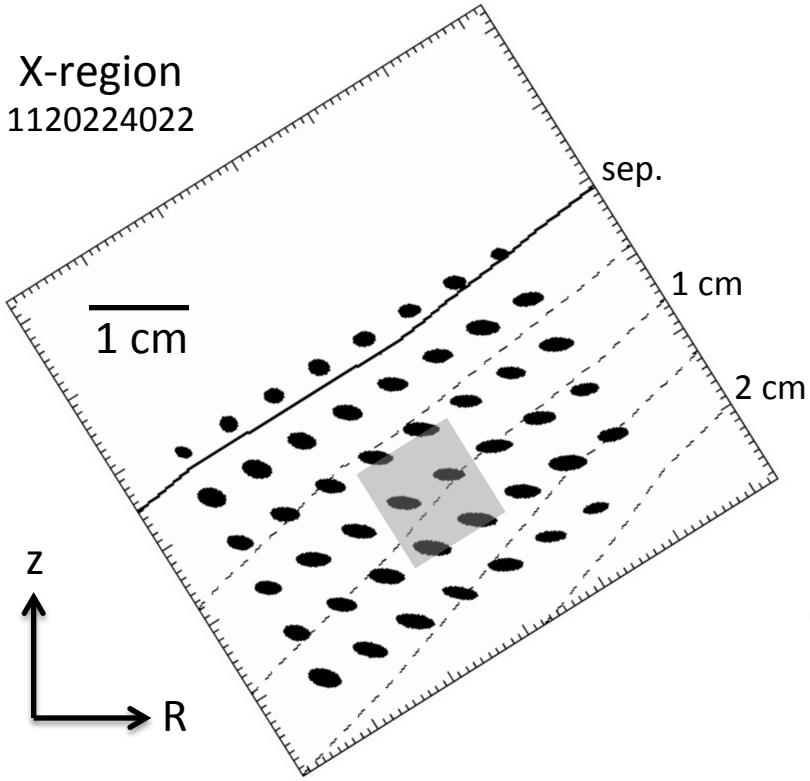
Typical Cross-Correlation Structures

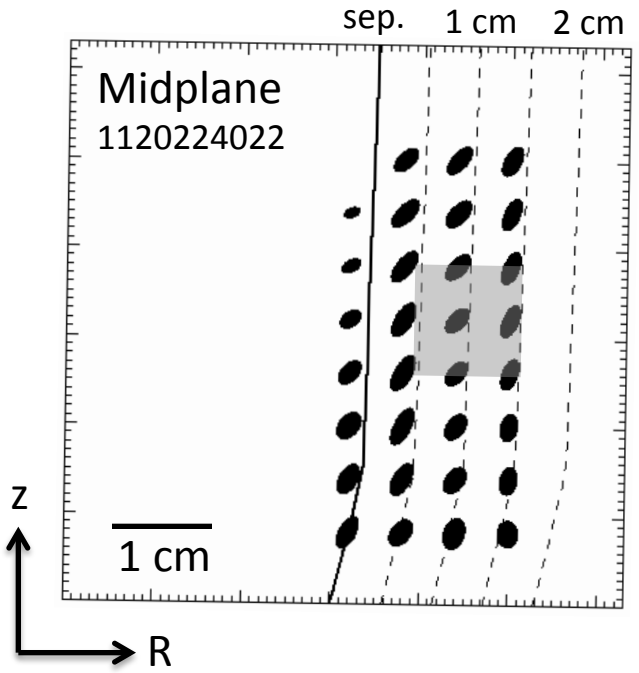
- Midplane correlation in SOL slightly tilted from flux surface
- X-region correlation in SOL elongated in major radius direction
- Small wave-like negative cross-correlations in many cases
- Similar results for both L-mode and H-mode plasmas



Cross-Correlation Structures in 2-D

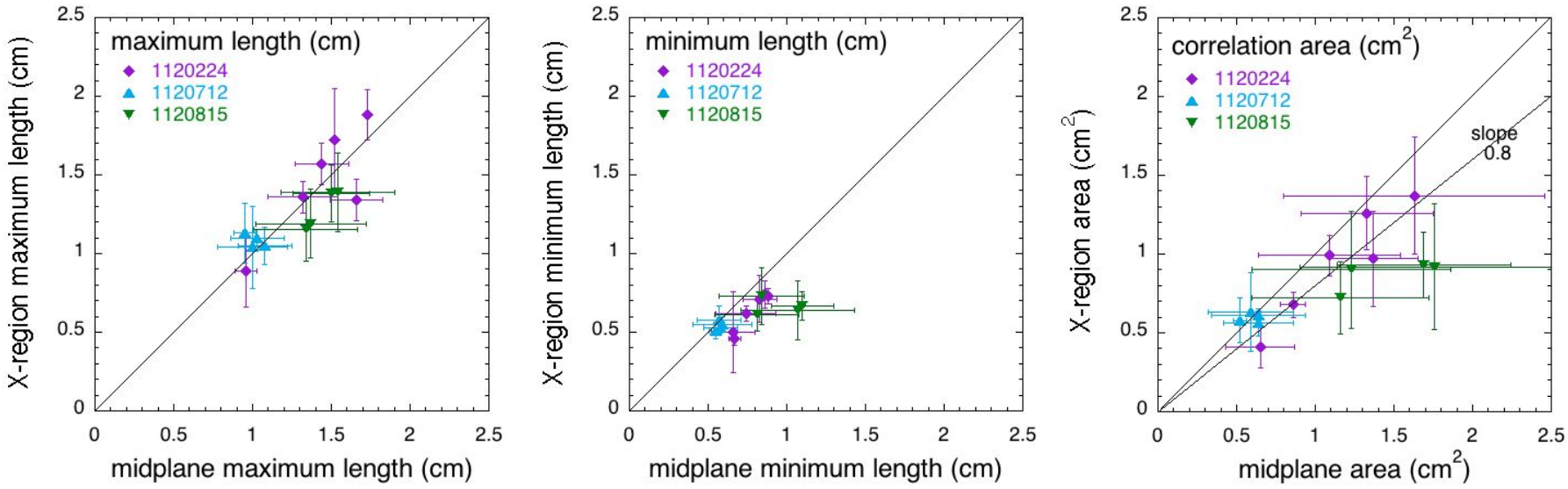
- Cross-correlation ellipses evaluated at correlation of 0.7
- Slow variation of size and tilt over 2-D view in both regions, where ellipses below reduced in size by x3 to avoid overlap
- Subsequent analyses for central gray regions near ρ = 1 cm





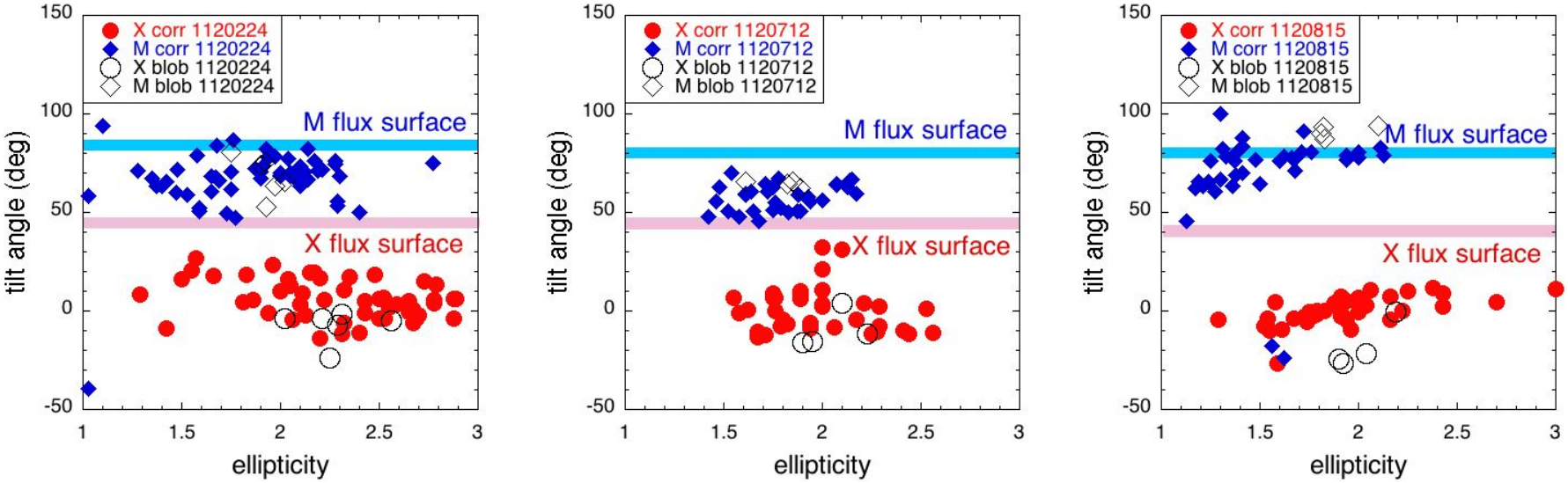
Spatial Correlation Sizes and Areas

- Maximum length of correlation ellipses similar in both views
- Minimum length of correlation ellipses smaller in X-region
- Area of correlation ellipses ~0.8 time smaller in X-region, as expected from magnetic field mapping between regions



Ellipticity and Tilt of Correlation Structures

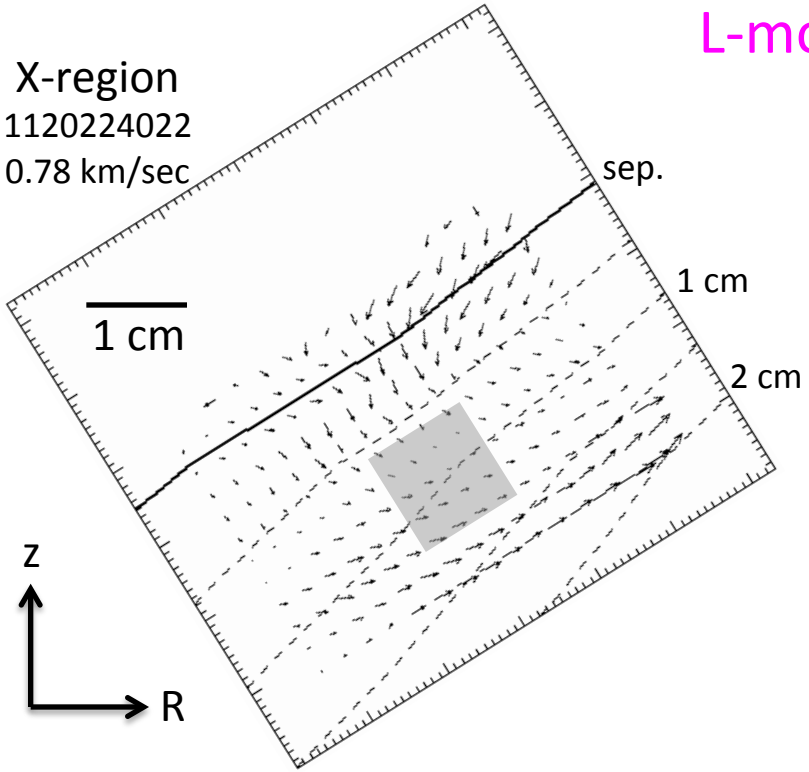
- Ellipticity of structures is slightly larger in X-region than midplane
- Tilt angle of structures very different in midplane and X-region
- Tilt angles measured with respect to major radius, with local flux surface tilt angles shown by horizontal lines

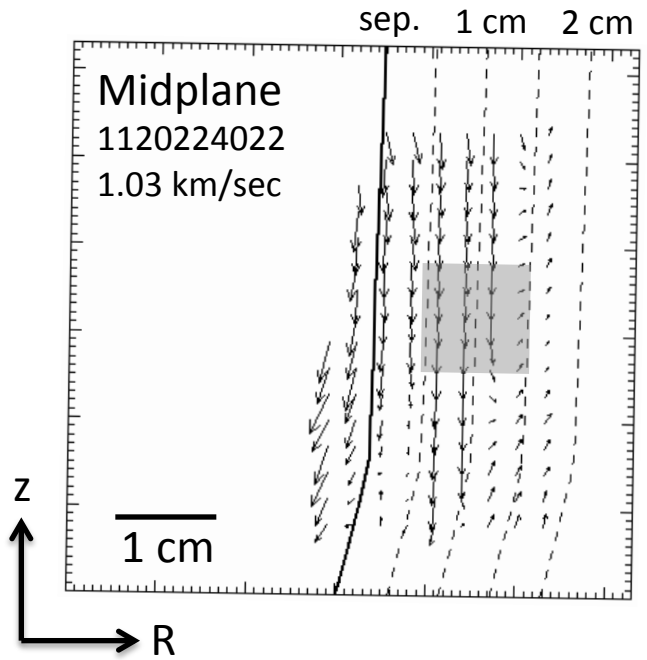


Turbulence Velocity Maps in 2-D

- Velocities derived from 2-D time-delayed cross-correlation analysis
- Turbulence velocities are different at midplane and X-region
- There is often small-scale structure to velocity in each region

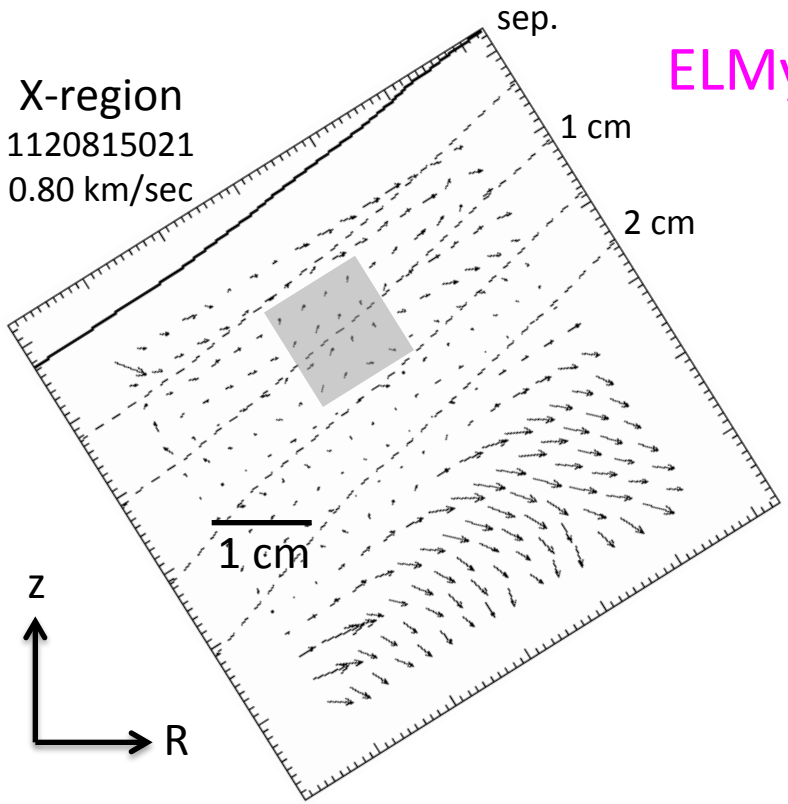
L-mode



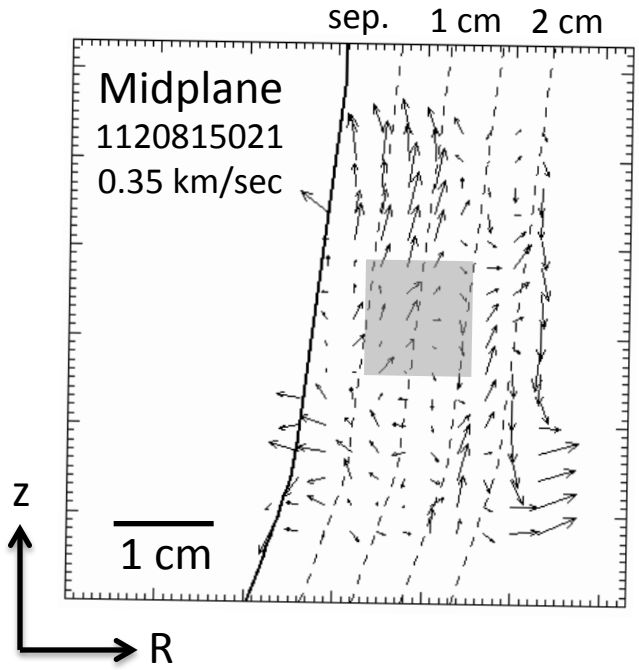


Turbulence Velocity Maps in 2-D…cont…

- Velocities derived from 2-D time-delayed cross-correlation analysis
- Turbulence velocities are different at midplane and X-region
- There is often small-scale structure in 2-D velocity in each region



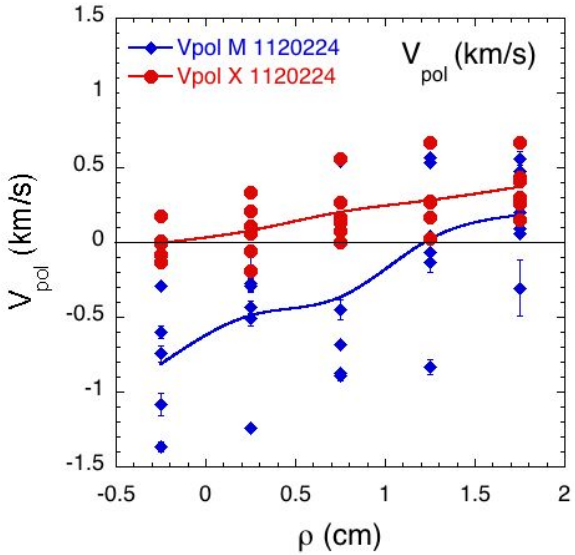
ELMy H-mode



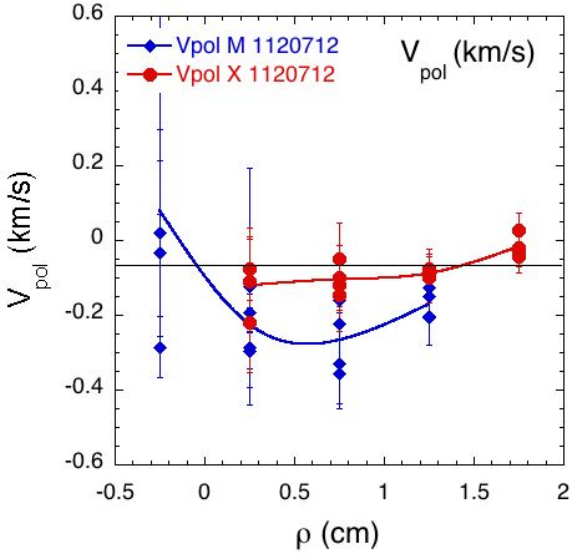
Radial Profiles of Average Poloidal Velocity

- These profiles are averaged over 0.5 cm radial zones in 2-D maps
- Different points are velocities for different shots in each run
- Poloidal velocities are usually different in midplane and X-region•

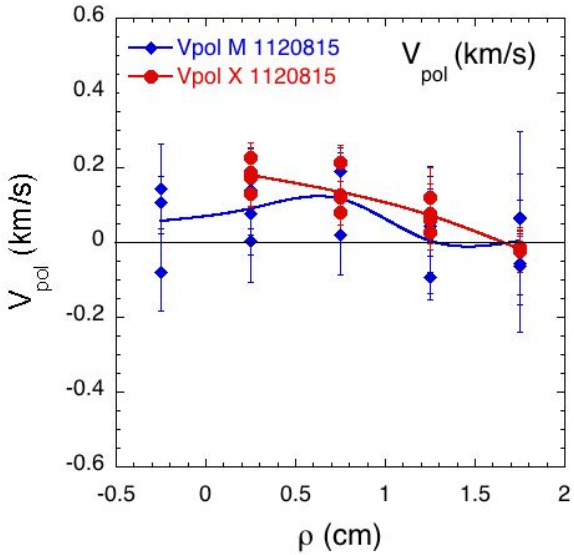
L-mode



Ohmic H-mode

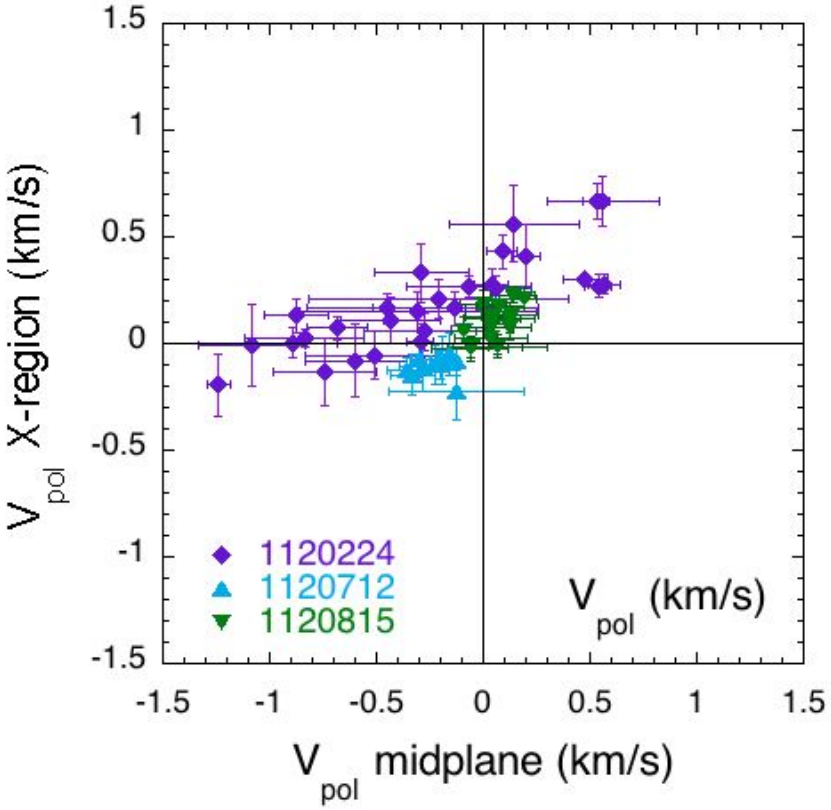


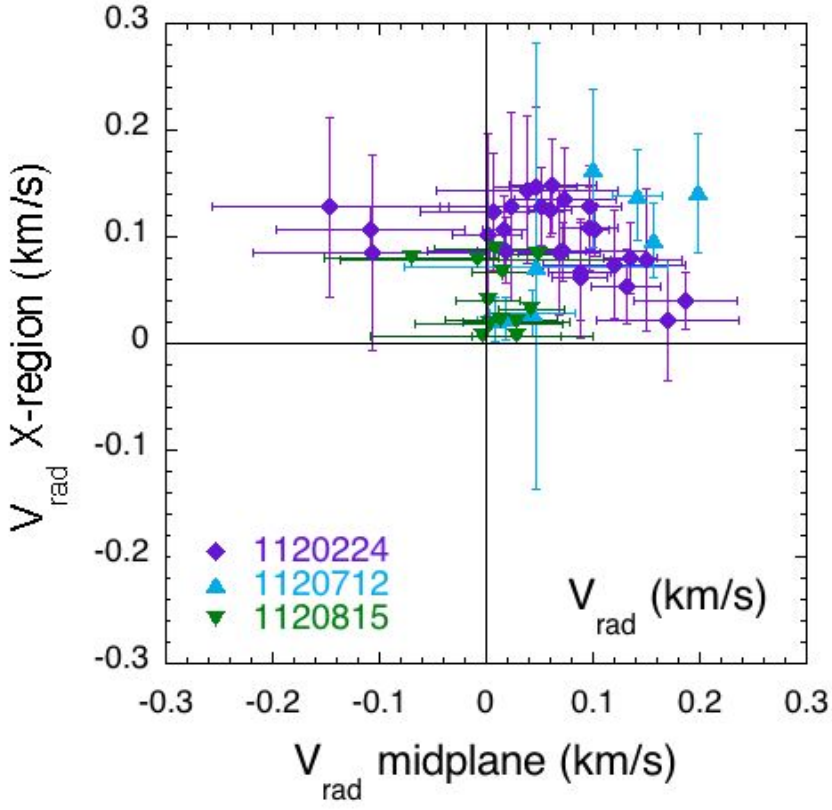
ELMy H-mode



Midplane vs. X-region Average Velocities

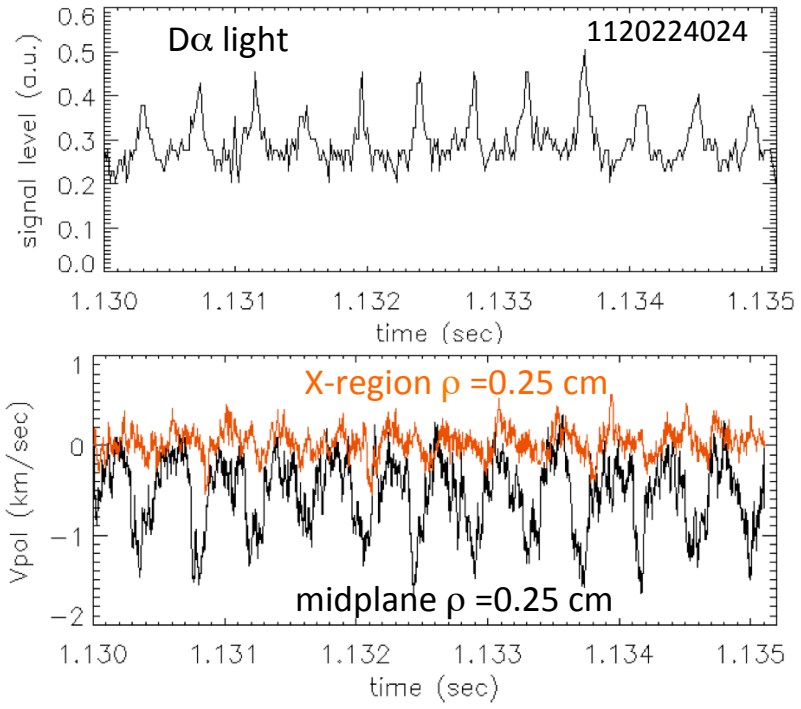
- These profiles are averaged over 0.5 cm radial zones in 2-D maps
- Sometime poloidal velocities are in a opposite poloidal directions
- Radial velocities outward and smaller than poloidal velocities

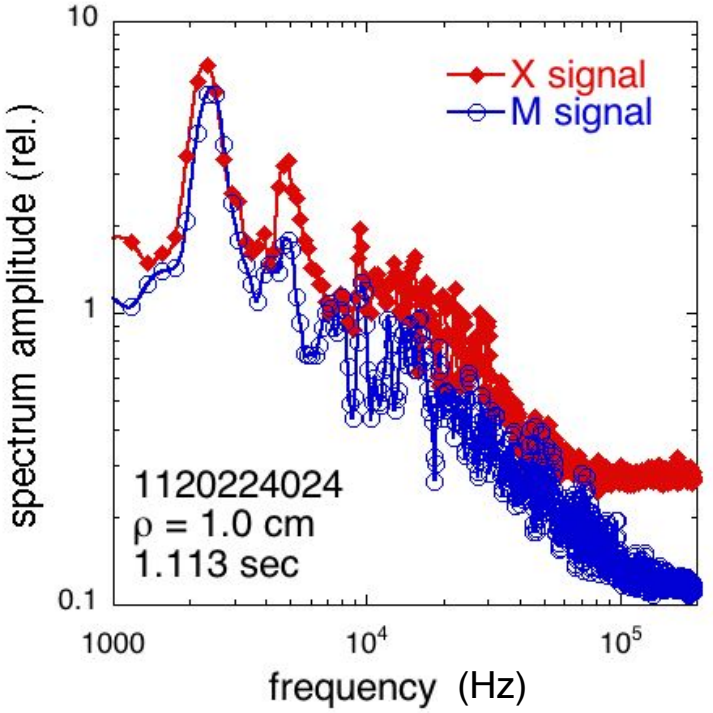




Edge Coherent Oscillations

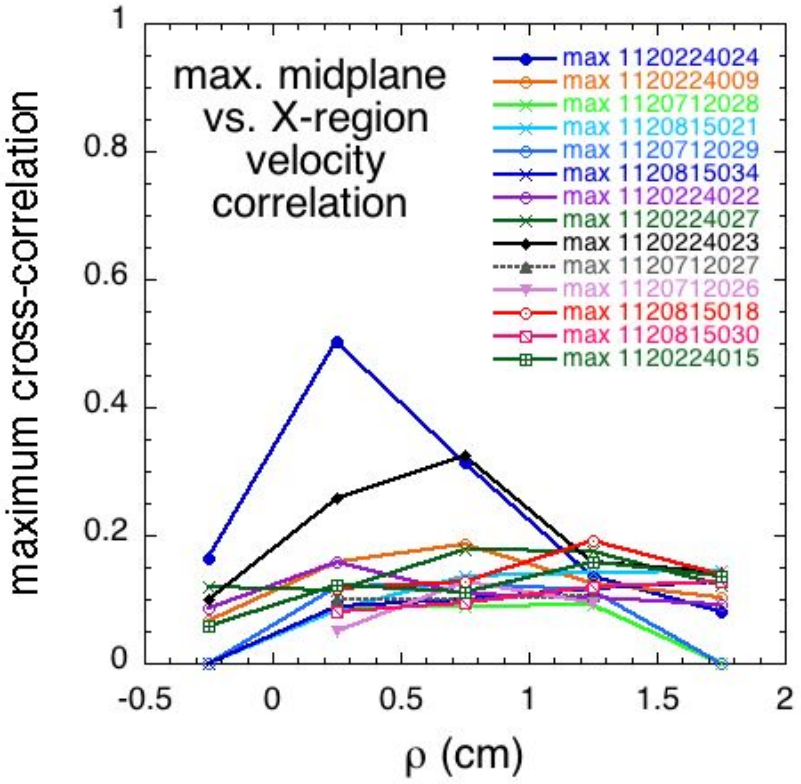
- Sometimes there are edge oscillations in Dα and in GPI signal level
- These are seen in poloidal velocity in both midplane and X-region
- These were seen only in run 1120224 at ~2-5 kHz (not MHD)





Correlation of Midplane vs. X-region Velocity

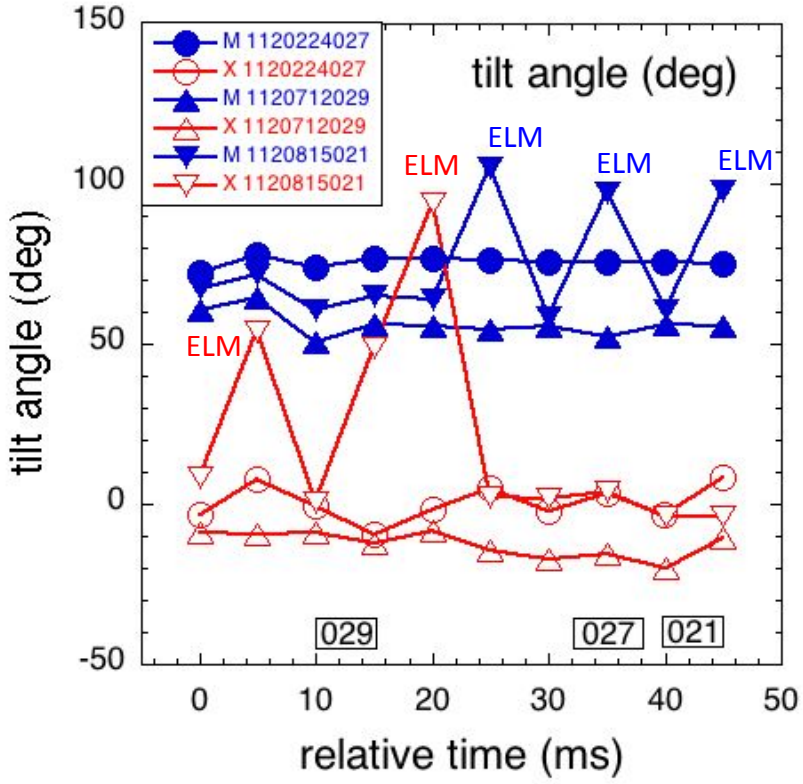
- Velocities in each region averaged over 0.5 cm radial zones
- Maximum time-delayed cross-correlation usually ≤0.15 (random)
- Only significant cross-correlation during edge coherent modes

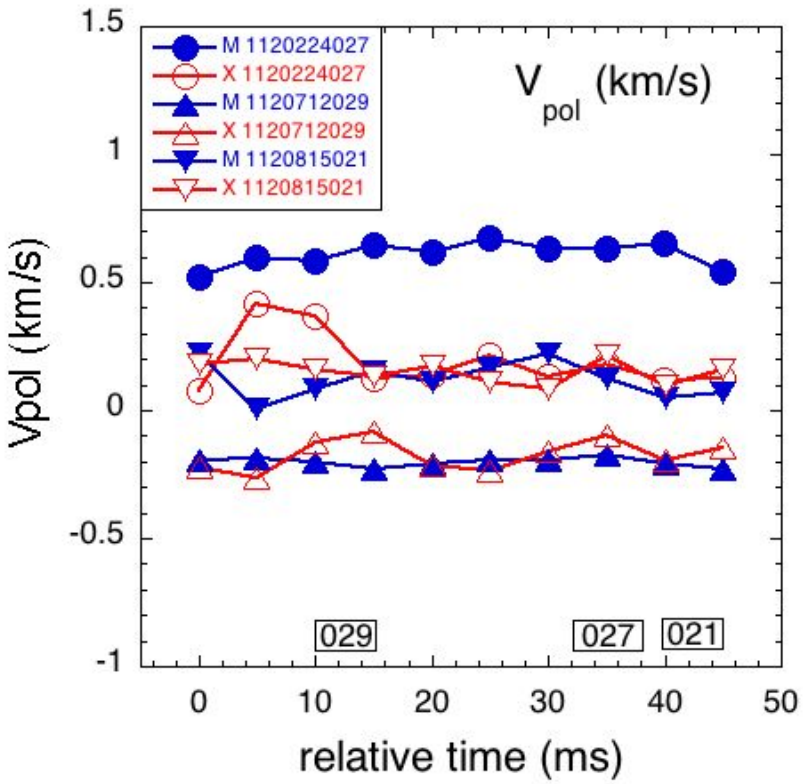


=> no evidence for long-range zonal flows in SOL

Longer Time Dependence of Turbulence

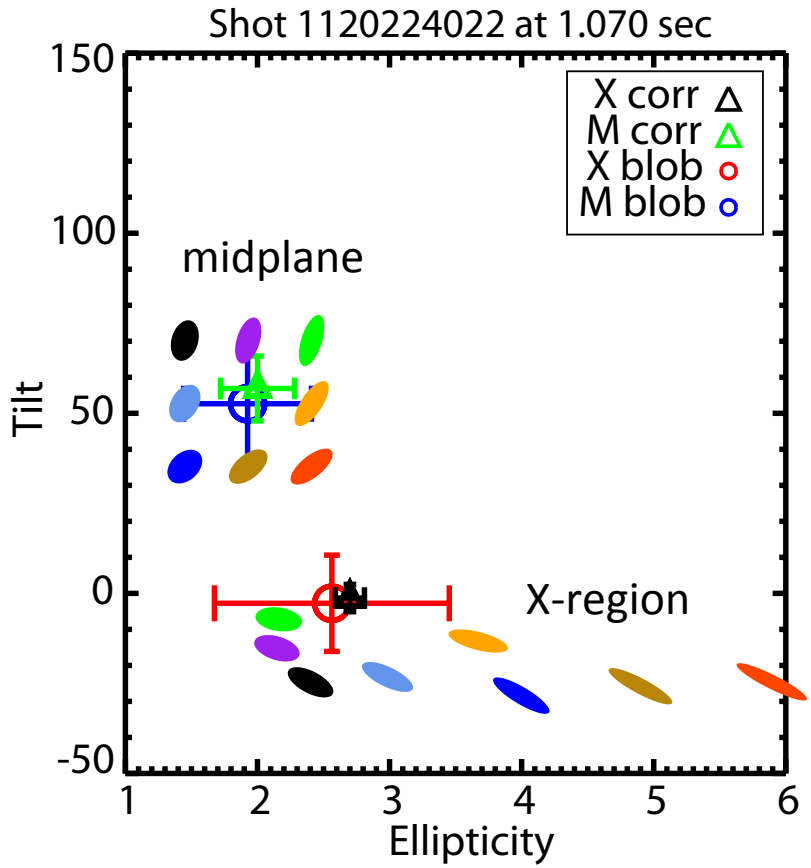
- Previous analyses were for 3-5 msec/shot, below 50 msec/shot
- No significant change in structure or velocity over 50 msec
- Exceptions are during ELMs and L-H transitions (not shown)





Comparison with Flux Tube Mapping

- Midplane tilt and ellipticity fit to ellipses, then mapped to X-region
- Measured X-region tilt and ellipticity are similar to mapping model

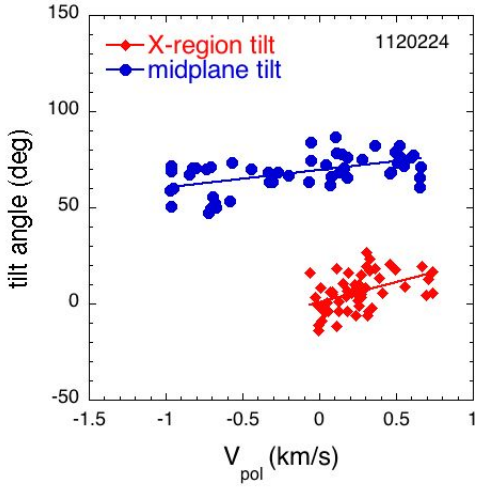


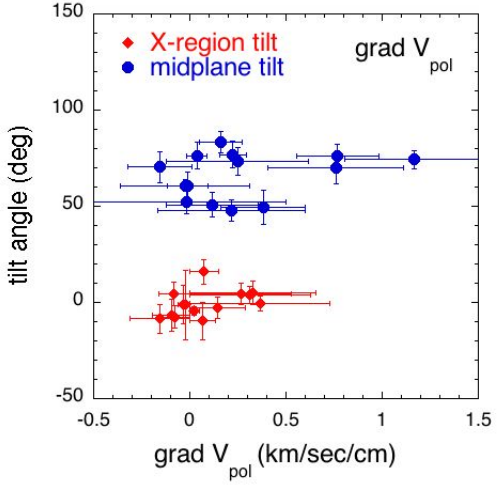
⇒ partial agreement with flux tube mapping model

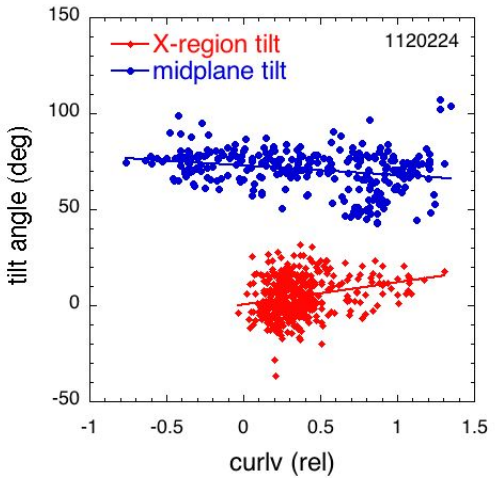
similar results for other shots and run days

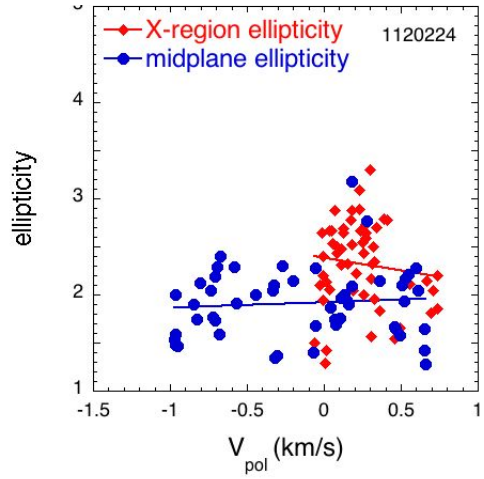
Turbulence Structure vs. V, grad V, curl V

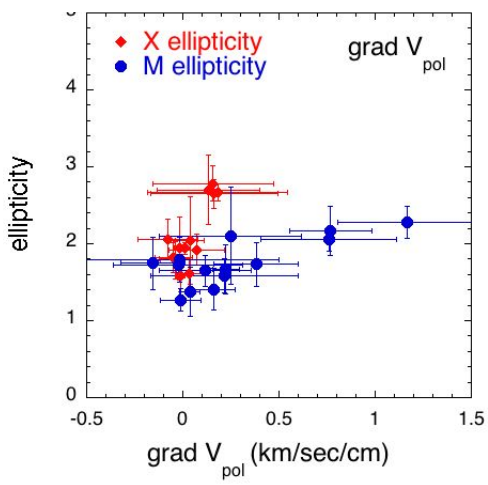
- Turbulence structure is roughly independent of the local poloidal velocity, and of the gradient or curl of local velocity

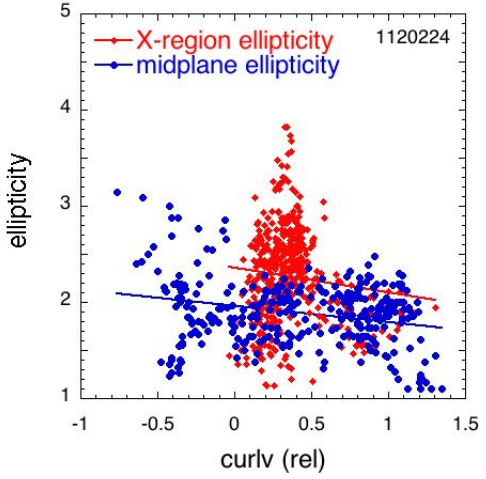












Some Unresolved Issues

- Effects of ICRF antenna electric fields on turbulence structure and velocity - need more data with no-RF and large outer gaps

- Reconcile high parallel cross-correlation along B field line found with incomplete fit to flux tube mapping model

- Reconcile velocities obtained by cross-correlation method with velocities obtained from slope of $S(\omega,k)$ spectra

Some Possible Future Directions

- Add other poloidal and toroidal GPI views, e.g. along a B field line
- Improve 3-D modeling of GPI gas puff using local plasma profiles
- Improve analysis to characterize 2-D structures and velocities
- Compare GPI results with other turbulence and flow diagnostics
- Explain SOL turbulence using first-principles 3-D simulations

Conclusions

- The *turbulence structure* is similar at midplane and X-point region
  - relative fluctuation levels and frequencies are similar
  - size and ellipticity of turbulence cross-correlation are similar
  - tilt angle of turbulence correlations are significantly different, but at least partially consistent with flux tube mapping

- The *turbulence velocity* is different at midplane and X-point region
  - time-averaged turbulence velocities are usually different
  - 2-D structure of time-averaged velocity is usually different
  - fluctuations in turbulence velocity are usually different