NSTX-U

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2-D turbulence cross-correlation functions in the edge of NSTX

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Lawrence Livermore National Laboratory

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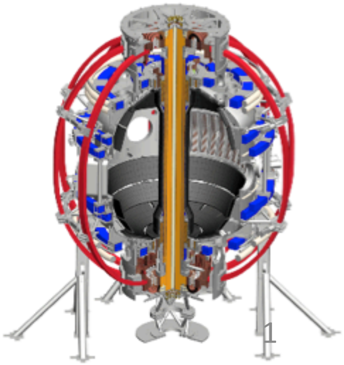


Motivations and Goals

- Characterize 2-D structure of edge turbulence as seen by GPI (gas puff imaging) in NSTX

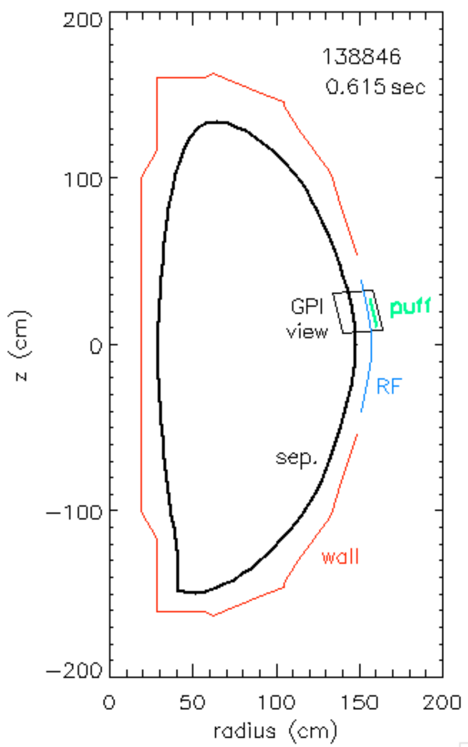
- Use zero-time delay correlation functions for 2-D structure (not time-delayed correlation functions for motion)

- Try to understand correlations results in terms of
  - B field angle alignment with GPI view direction
  - magnetic field shearing of edge flux tubes
  - poloidal flow shearing of turbulence blobs
  - positive blob vs. negative hole correlations
  - neutral shadowing in GPI diagnostic

- Compare results with simulations (not in this poster)

GPI Geometry in NSTX

- GPI views 2-D region above outer midplane near separatrix
- GPI measures neutral Dα line emission from local gas puff
- GPI view aligned as close as possible to local B field direction



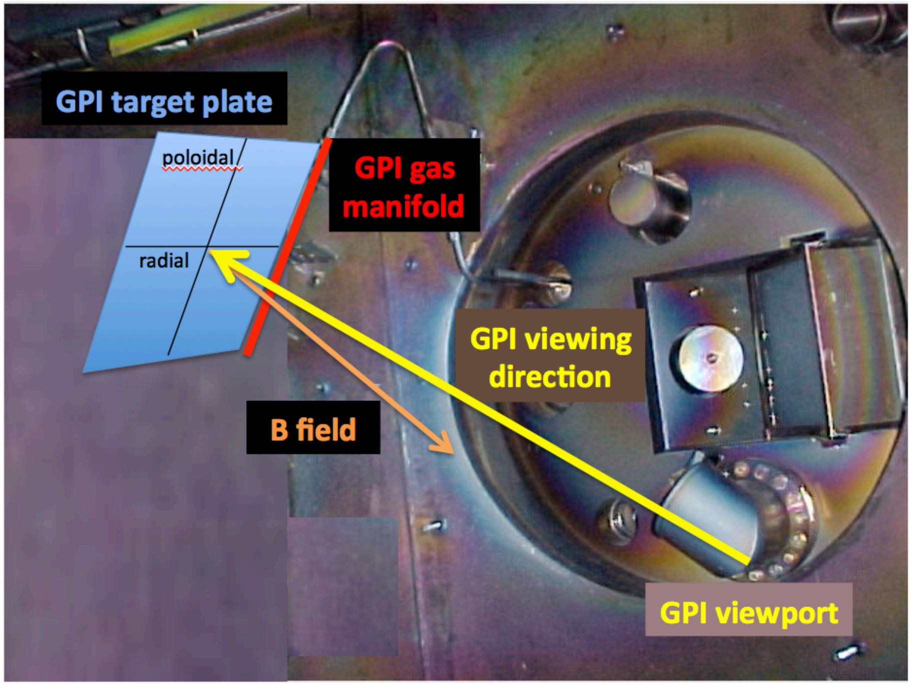
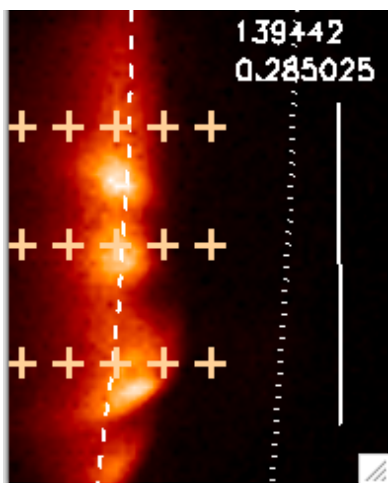


Image Plane in GPI Camera View

- Image region 24 cm radial x 30 cm poloidal near separatrix
- Image region fixed in space as separatrix moves with shots
- Choose 5x3 spatial grid for analysis of 2-D correlations (+)

inward separatrix

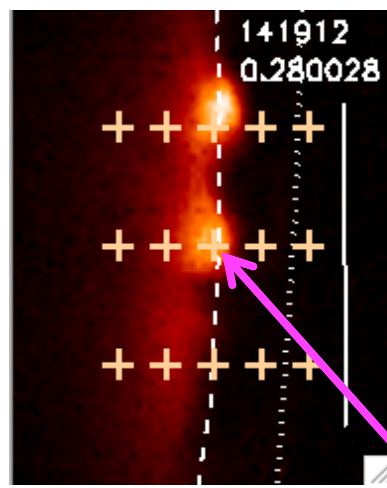
poloidal



radial

outward separatrix

poloidal



radial

5x3 grid point array (+)

radius r = 0 @ separatrix
radius r = ± 3 cm from sep.
radius r = ± 6 cm from sep.
poloidal p = 0 cm (middle)
poloidal p = ±7.5 cm off mid.

(r,p) = (0,0) grid point at separatrix and vertical middle of image

GPI Database for This Analysis

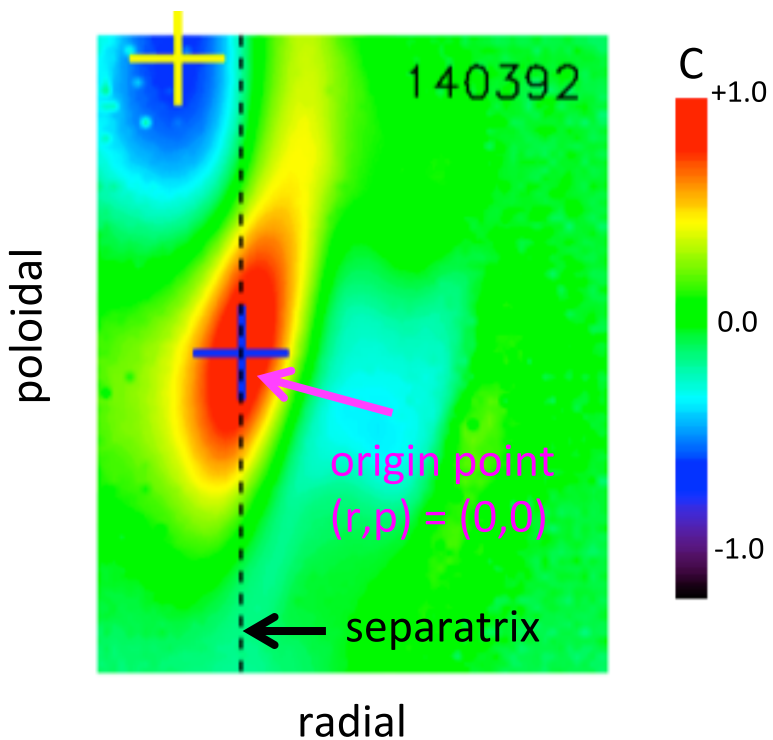
- Broad range of shot types from 2010 database (Zweben PPCF ’15), with range of vertical B field angles θ_z (deg) at GPI center

	shot	time (sec)	type	B_0(T)	I(MA)	I/B	R_{sep} (cm)	P_{aux} (MW)	W (MJ)	θ_z (deg)	Θ
1	138122	0.230	OH	0.44	0.93	2.10	148	0.0	35.0	27.8	10.1
2	138126	0.245	OH	0.44	0.93	2.10	148	0.0	41.7	29.2	8.8
3	138844	0.615	H	0.44	0.82	1.86	151	3.8	215	38.9	5.9
4	138848	0.615	H	0.44	1.0	2.31	148	3.8	259	42.7	7.9
5	139045	0.415	H	0.49	1.0	2.10	150	5.9	244	38.5	6.2
6	139050	0.415	H	0.54	1.1	2.09	149	6.0	307	37.4	6.0
7	139289	0.315	H	0.49	0.83	1.69	149	3.0	133	32.2	9.0
8	139442	0.290	L	0.54	1.1	2.10	148	2.0	113	32.9	8.9
9	139444	0.265	OH	0.34	0.68	1.98	148	0.0	47.2	33.2	8.6
10	139446	0.225	OH	0.34	0.71	2.06	148	0.0	34.7	31.7	8.1
11	139501	0.515	H	0.47	0.92	1.95	147	2.0	164	35.5	7.0
12	139951	0.365	H	0.44	0.94	2.11	147	5.0	219	39.4	7.3
13	140392	0.545	H	0.49	0.84	1.70	146	4.0	223	36.4	8.6
14	140623	0.265	H	0.47	0.94	1.98	148	1.9	130	32.8	9.7
15	141270	0.475	H	0.44	1.0	2.33	146	3.8	221	39.5	8.6
16	141741	0.215	OH	0.41	0.72	1.79	149	0.0	26.5	26.0	11.8
17	141912	0.285	OH	0.44	0.91	2.05	152	0.0	53.4	30.4	6.1
18	141984	0.230	L	0.44	0.93	2.09	154	1.1 (RF)	57.1	30.7	5.1
19	142220	0.285	L	0.44	0.81	1.83	149	0.96	69.2	31.4	8.5
20	142270	0.375	L	0.44	0.81	1.82	151	1.0	66.7	32.1	6.3

Typical 2-D Correlation Function

- Starting from origin point p_1, cross-correlation C to point p_2 is:

$$C(\vec{p}_1,\vec{p}_2) = \frac{\langle [S(\vec{p}_1;i) - \langle S(\vec{p}_1;i)\rangle] \, [S(\vec{p}_2;i) - \langle S(\vec{p}_2;i)\rangle] \rangle}{\left\{ \langle [S(\vec{p}_1;i) - \langle S(\vec{p}_1;i)\rangle]^2 \, [S(\vec{p}_2;i) - \langle S(\vec{p}_2;i)\rangle]^2 \rangle \right\}^{1/2}}$$



this normalized C is in the range -1 to +1

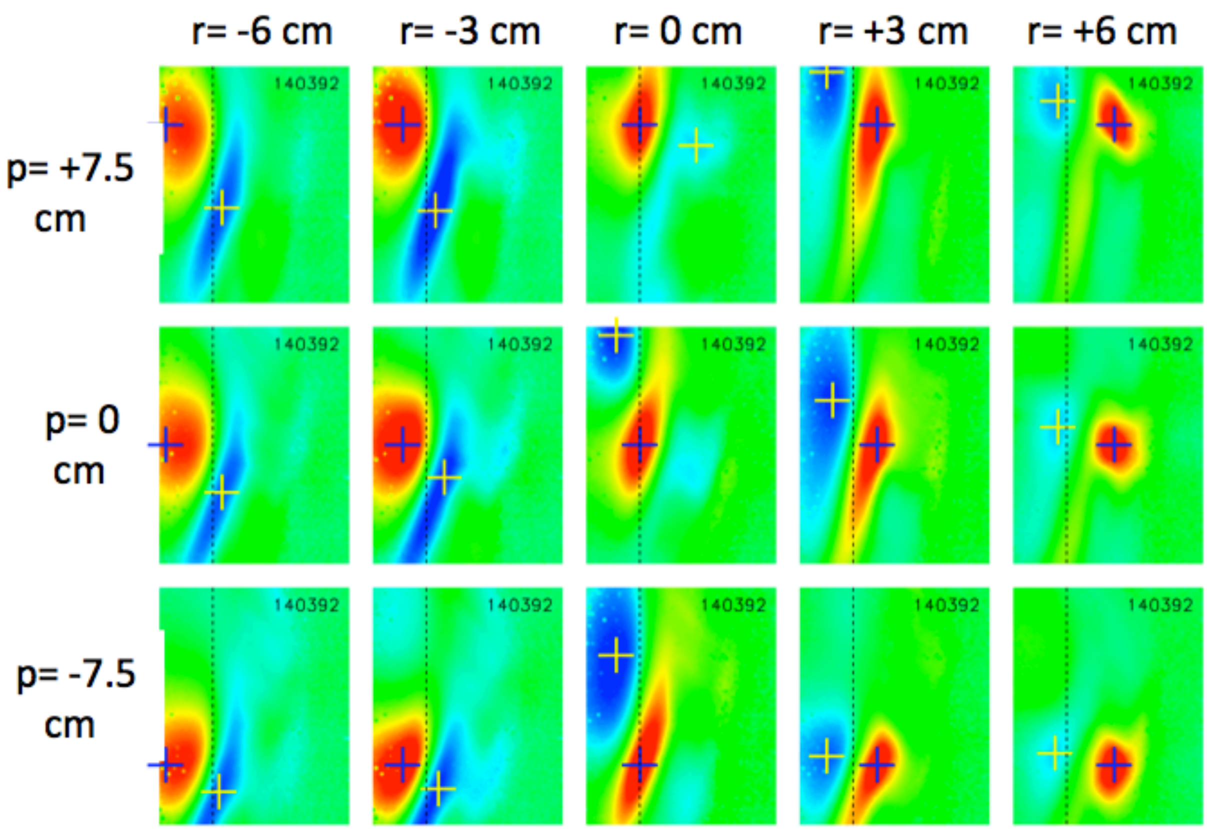
correlation origin point is shown by blue + symbol, with red regions having high positive correlation C > 0.5

minimum negative correlation is shown by yellow cross, with dark blue regions having high negative correlation C < -0.5

green regions are near-zero correlation

Typical 2-D Correlation Functions Over Grid

- Significant variation of correlation patterns vs. origin radius “r”, and some variations vs. poloidal origin coordinate “p”



15 origin points

shot #140392
B=0.49 T
I = 0.84 MA
P = 4 MW NBI

Analysis of 2-D Correlation Functions

- Make database of 20 shots x 15 grid points/shot = 300 points
  - include global and local edge data from these shots

- Fit ellipse to each 2-D correlation function at C= 0.8 ± 0.005
  - calculate ε = ellipticity (major/minor axis of ellipse fit)
  - calculate φ = tilt angle of ellipse (ccw from radially outward)
  - eliminate bad fits, e.g. at edges (237/300 points remain)

- Quantify negative cross-correlation regions in two ways
  - minimum negative cross-correlation and its location
  - total negative correlation / total positive correlation

Average Results of Correlation Database

For database of 237 elliptical fits and 300 negative correlations from 20 shots of H-mode, L-mode and Ohmic plasmas:

- Average ellipticity ε = 2.2 ± 0.9 (standard deviation)
- Average tilt angle φ = 87 ± 34º (poloidal direction is 90º)
- Minimum negative correlation cmin = -0.30 ± 0.15
- Total ratio of correlations neg/pos = 0.25 ± 0.25

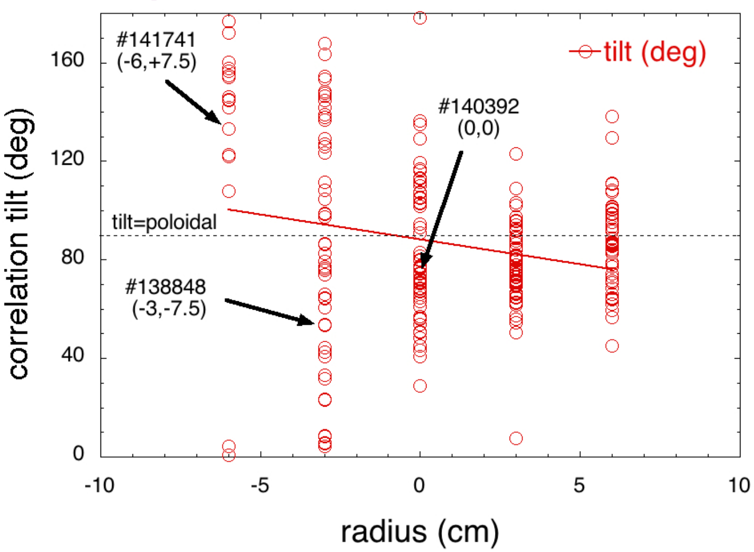
Thus there was significant scatter in these results !
What caused this variation ?

Spatial Variations of Correlation Tilt

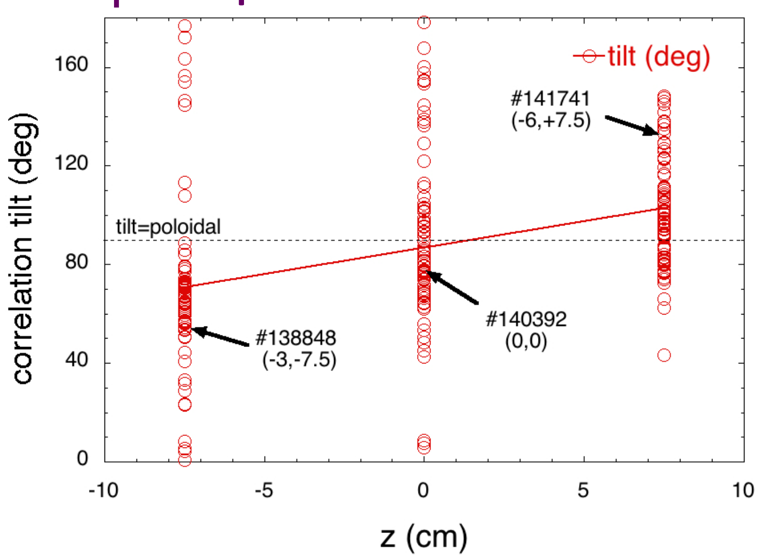
- No significant variation of tilt angle φ with radial coordinate, but wide scatter from -6 cm to +6 cm from separatrix

- Fairly clear increase in tilt angle φ with poloidal coordinate, with mainly φ < 90º at bottom and φ > 90º at top

φ vs. radial coordinate



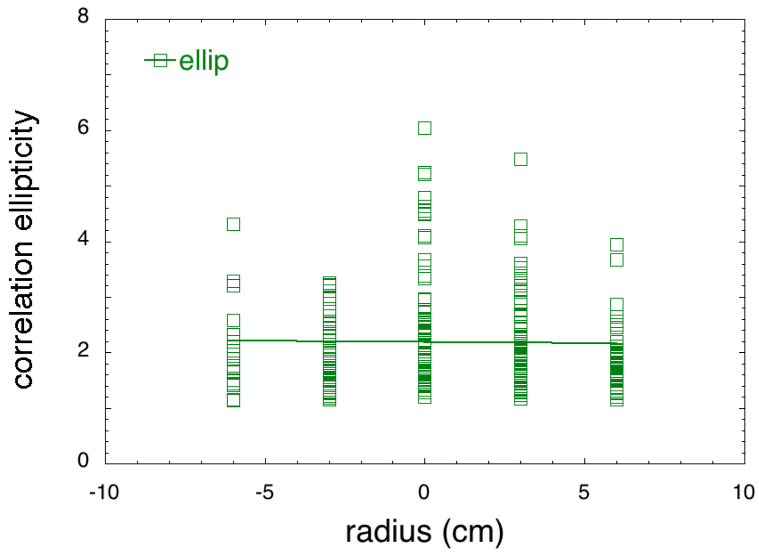
φ vs. poloidal coordinate



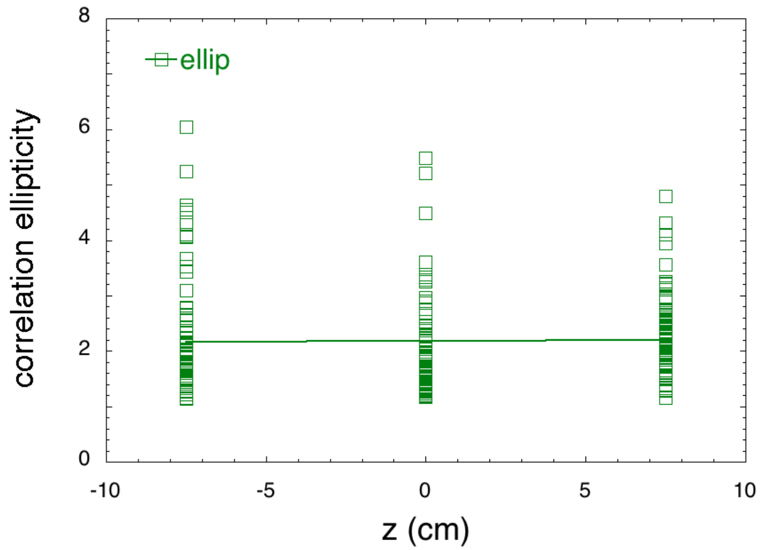
Spatial Variations of Correlation Ellipticity

- No significant variation of ellipticity ε with radial coordinate or poloidal coordinate from r= -6 cm to +6 cm from separatrix, or from p= -7.5 cm below to +7.5 cm above middle of image

ε vs. radial coordinate



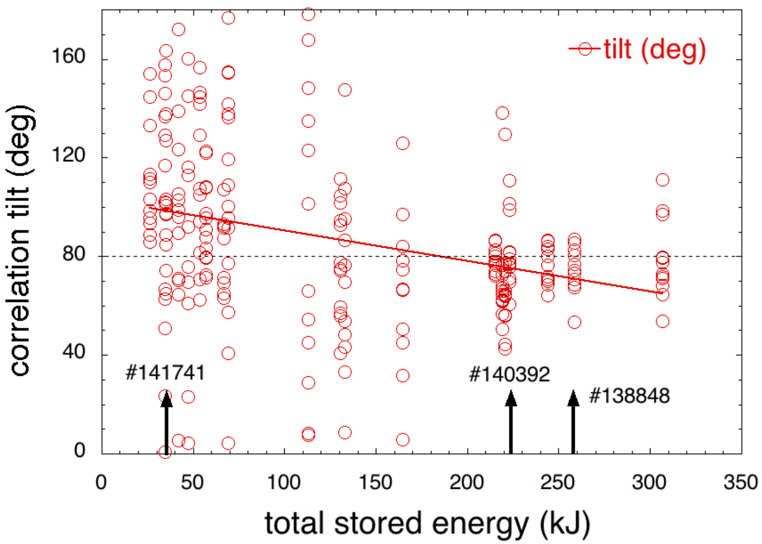
ε vs. poloidal coordinate



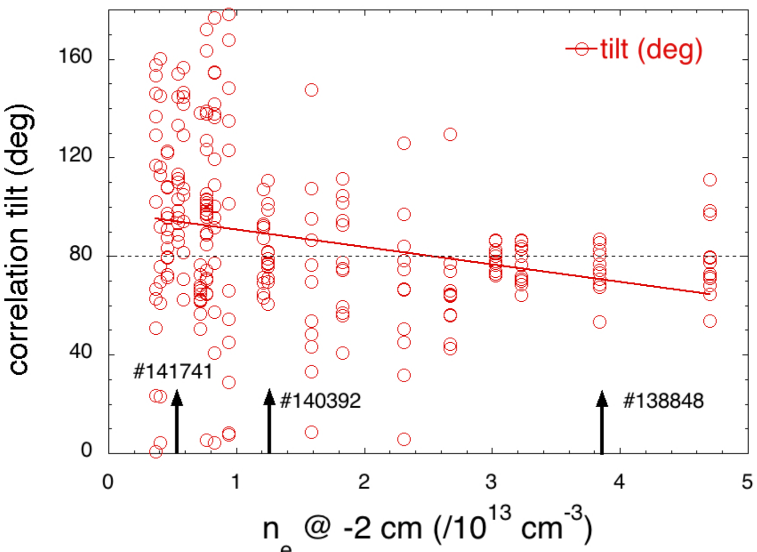
Plasma Variations of Correlation Results

- Tilt angles decrease slightly with stored energy and edge density
- Ellipticity increases slightly with stored energy and edge density
- Little or no variations with separatrix location, edge T_e, q95, κ, Li, or local turbulence correlation lengths or velocities

φ vs. stored energy

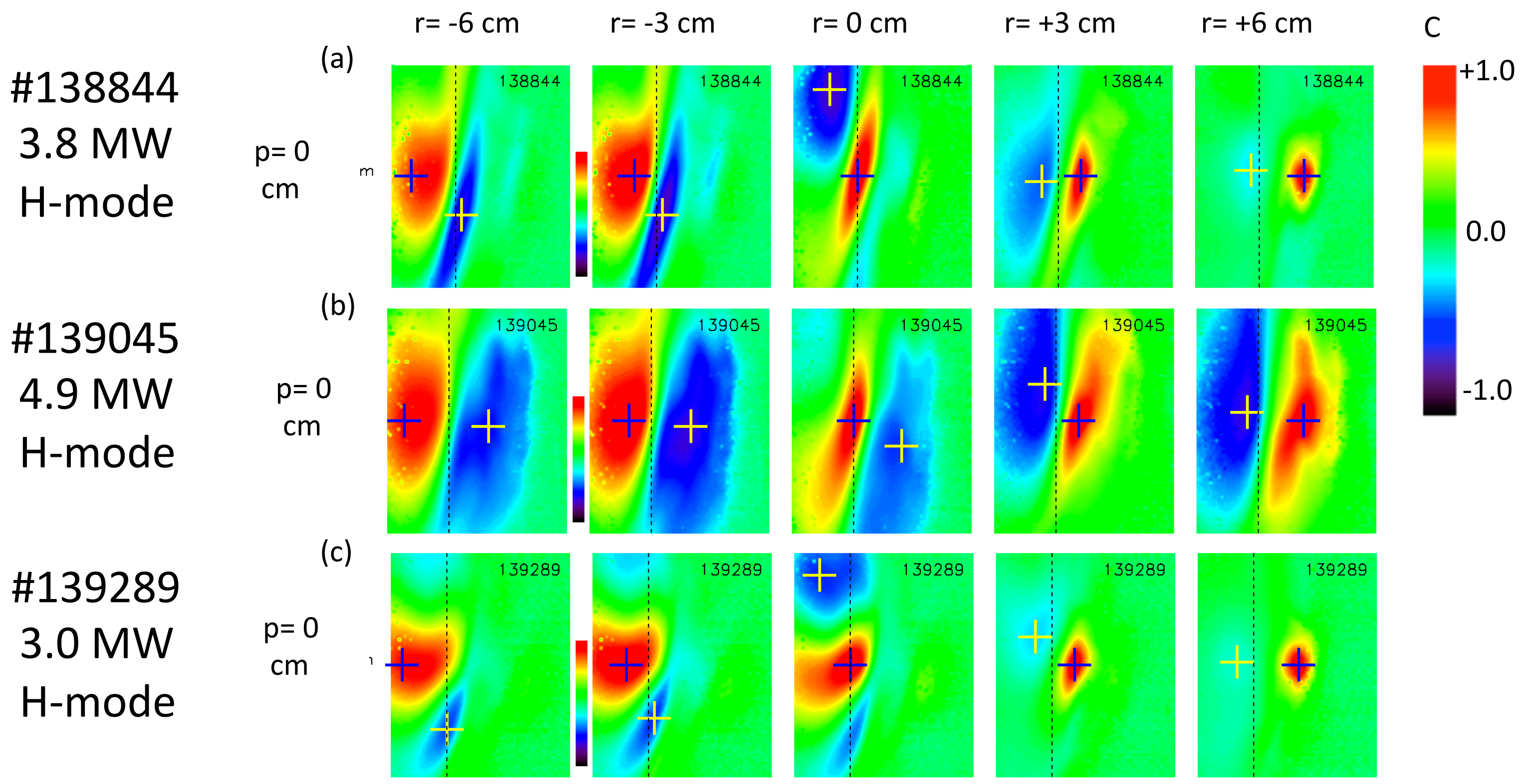


φ vs. edge density



Examples of Negative Correlation Patterns

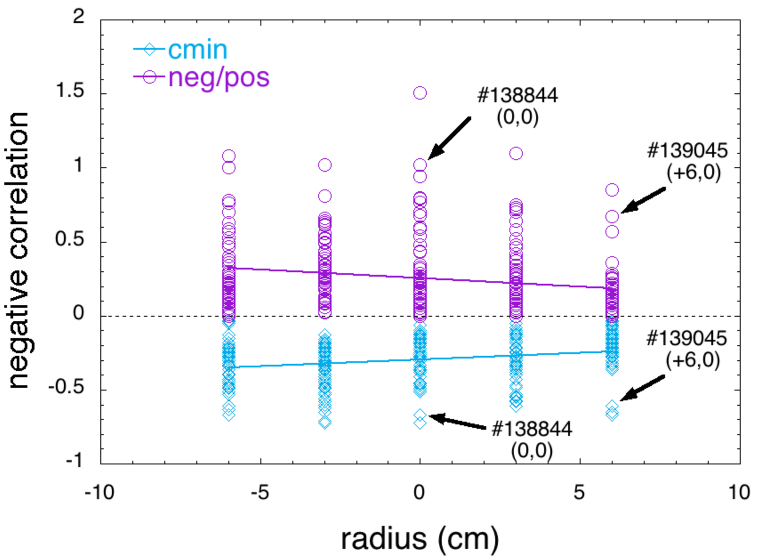
- Wide variety of negative correlation patterns, even among shots of a given type, e.g. H-mode (p=0 shown below)



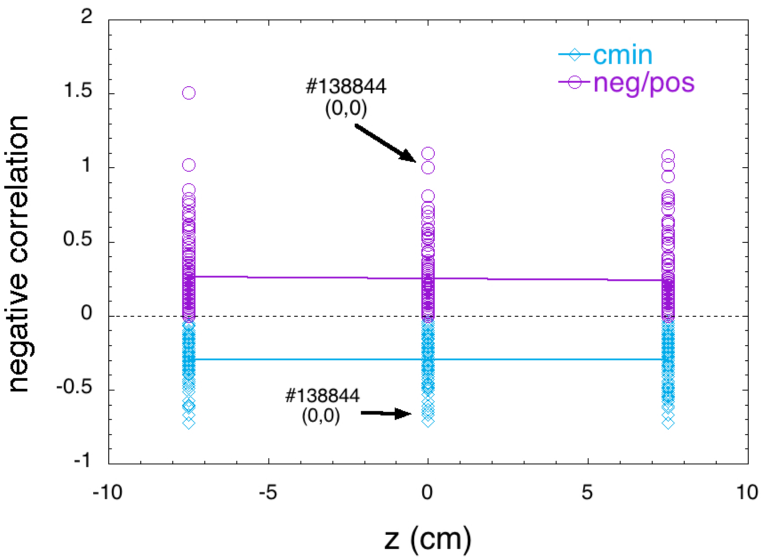
Spatial Variations of Negative Correlations

- Some decrease in cmin and neg/pos with increasing radius
- No variation of cmin or neg/pos with poloidal coordinate

negatives vs. radial



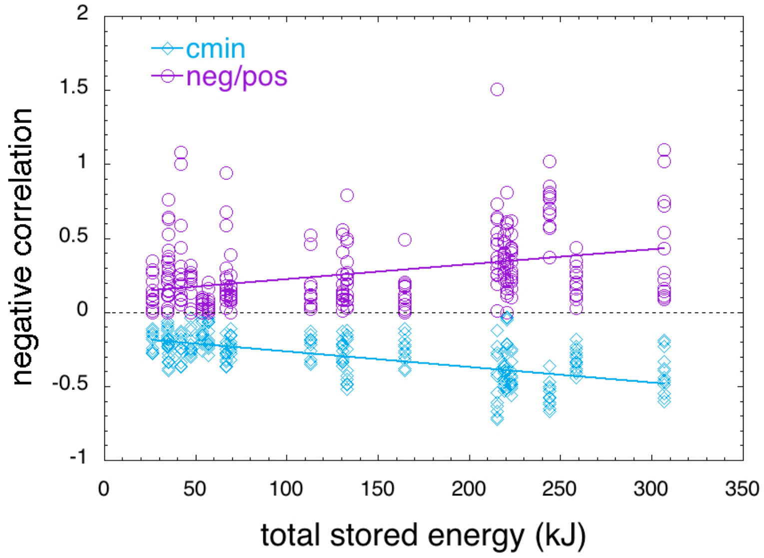
negatives vs. poloidal



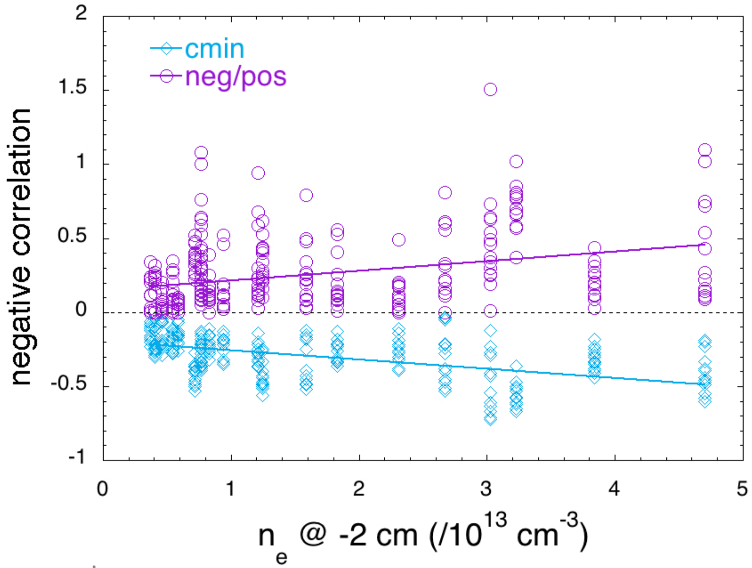
Plasma Variations of Negative Correlations

- Some increase in cmin and neg/pos with total stored energy
- Some increase in cmin or neg/pos with edge density
- Little or no variations with separatrix location, edge T_e, q95, κ, Li, or local turbulence correlation lengths or velocities

negatives vs. stored energy

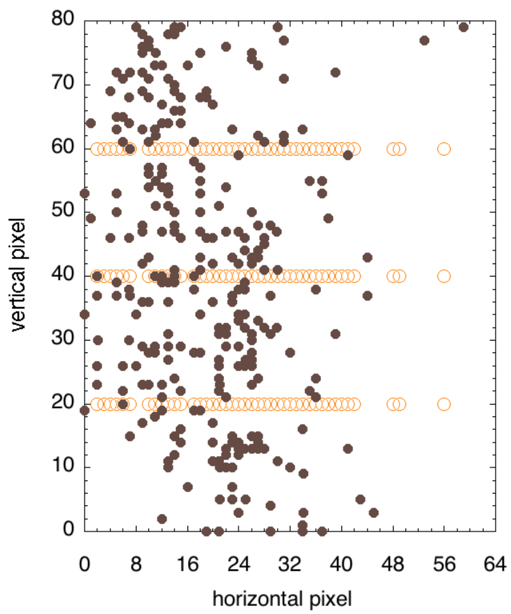


negatives vs. edge density



Location of Largest Negative Correlation

- Largest negative correlations "cmin" are widely distributed over image (probably some located outside its edges)
- Observed cmin locations cluster ~ 5-10 cm from origin point above/inside or below/outside, especially for cmin < -0.3

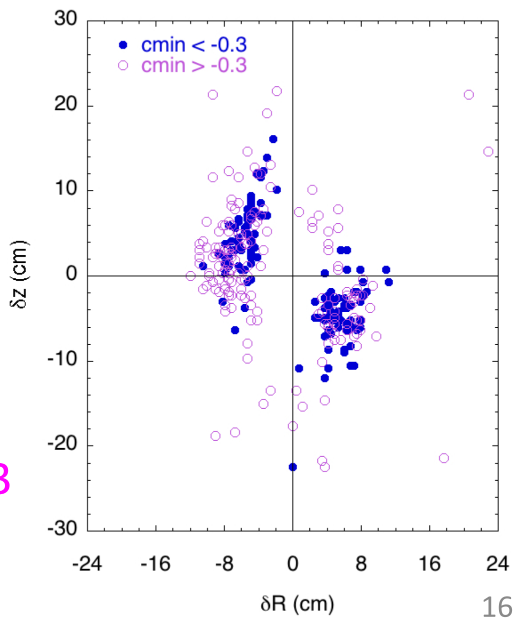


brown points are locations of cmin within GPI image

orange circles are locations of correlation origin points

blue points are distance of cmin from origin for cmin < -0.3

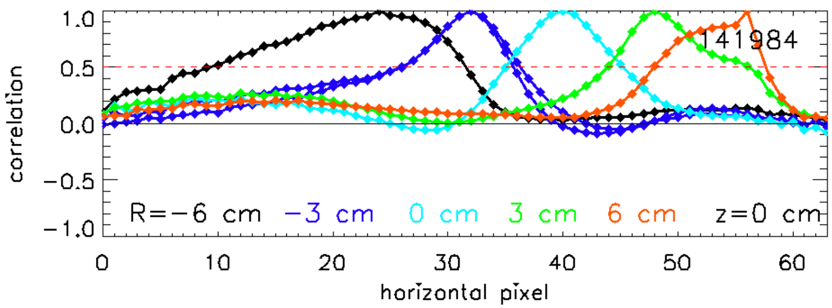
purple circles for cmin > -0.3

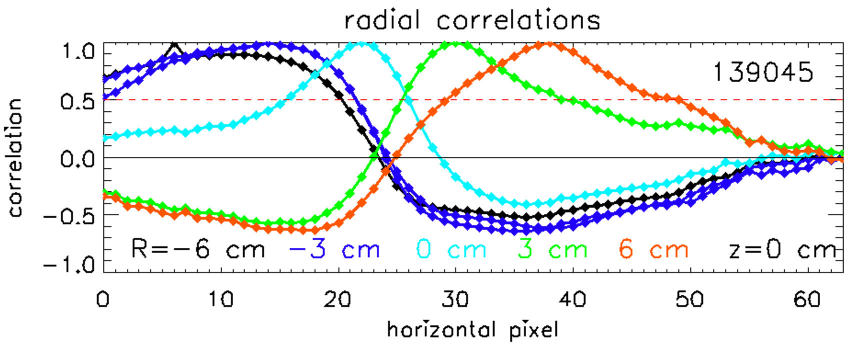


Shapes of 2-D Correlation Functions

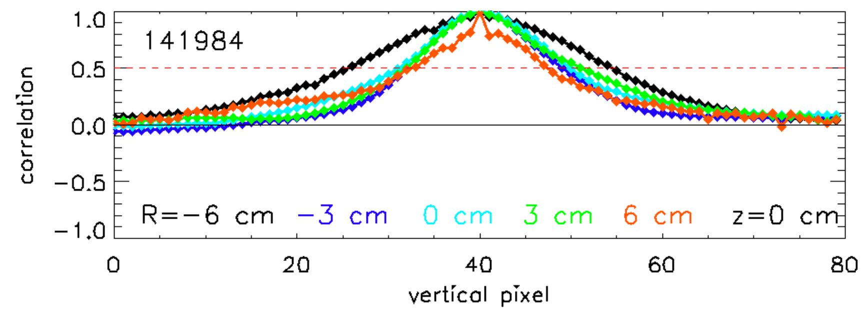
- Radial correlation functions sometimes have dipole-like shape
- Poloidal correlation functions usually have Gaussian-like shape

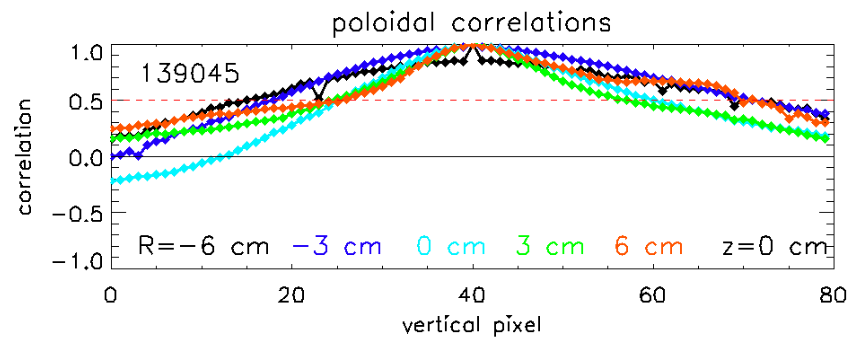
Radial correlation shapes





Poloidal correlation shapes





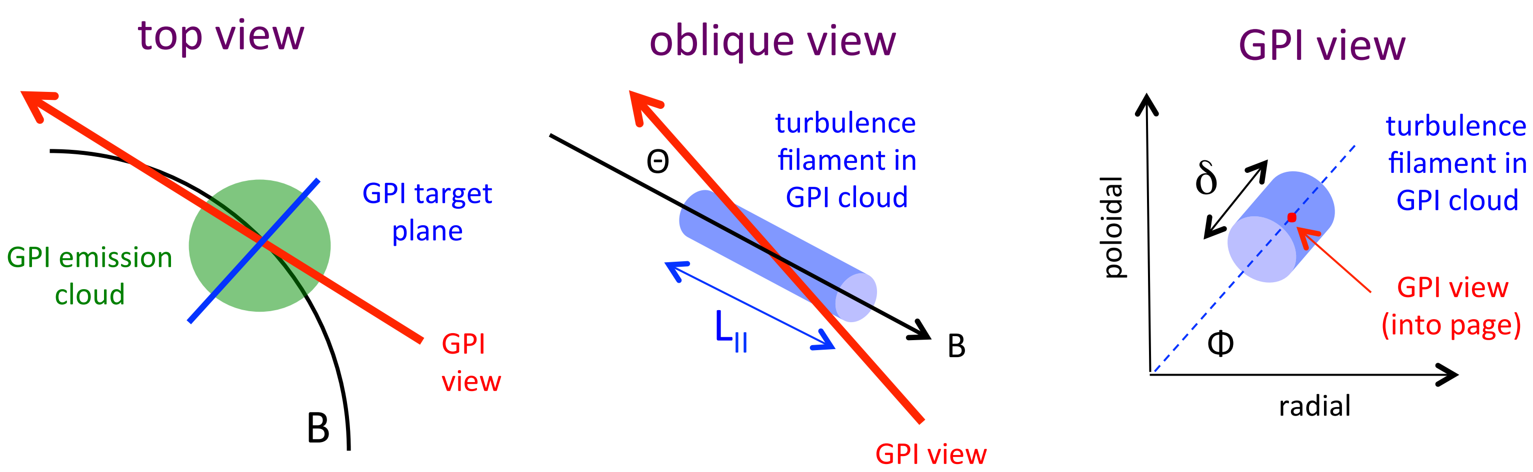
Possible Causes of Observed Variations

- Several mechanisms may affect the 2-D correlation pattern:
  - B field misalignment with GPI view direction
  - magnetic field tilting of edge flux tubes
  - poloidal flow shearing of turbulence
  - blob vs. negative hole correlations
  - neutral shadowing in GPI diagnostic

- Observed results might be a combination of all these factors, in addition to intrinsic variations in correlation functions with edge plasma parameters

Smearing Due to B Field Misalignment

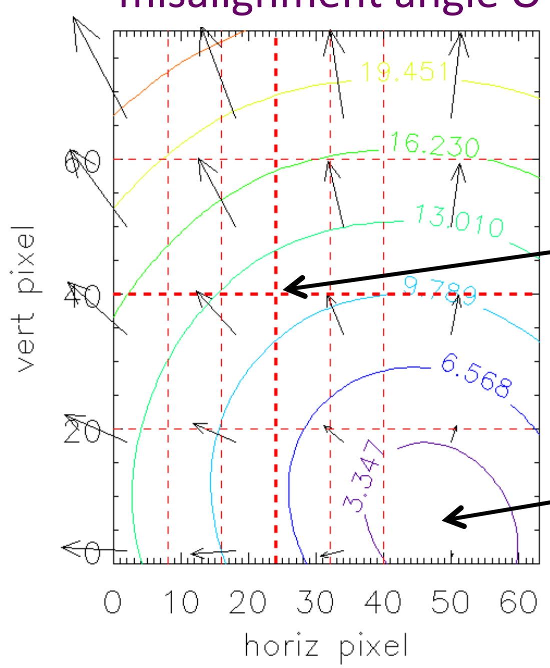
- 2-D structure will be smeared along misalignment direction Φ
- Smearing length $\delta \sim L_{||} \tan \Theta$, where $L_{||} \sim 12$ cm (from DEGAS2) and Θ = misalignment angle between GPI view and local B



Example of B Field Misalignment

- Range of misalignment angle Θ depends on shot and location within image, typically Θ ~ 5-12º at central grid point
- For worst aligned shot (#141741), local B field direction Φ is largely correlated with tilt of 2-D correlation function

misalignment angle Θ

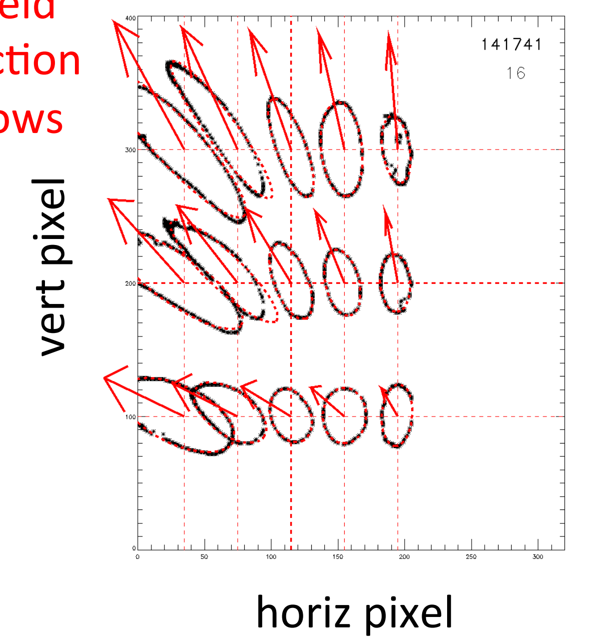


center grid alignment (Θ ~ 12º)

perfect alignment (Θ ~ 0º)

misalignment direction vs. 2-D correlation ellipses

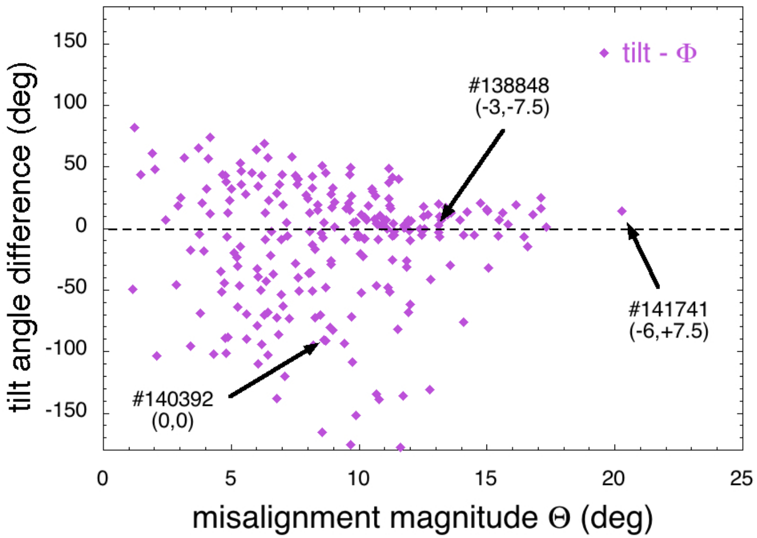
B field direction arrows



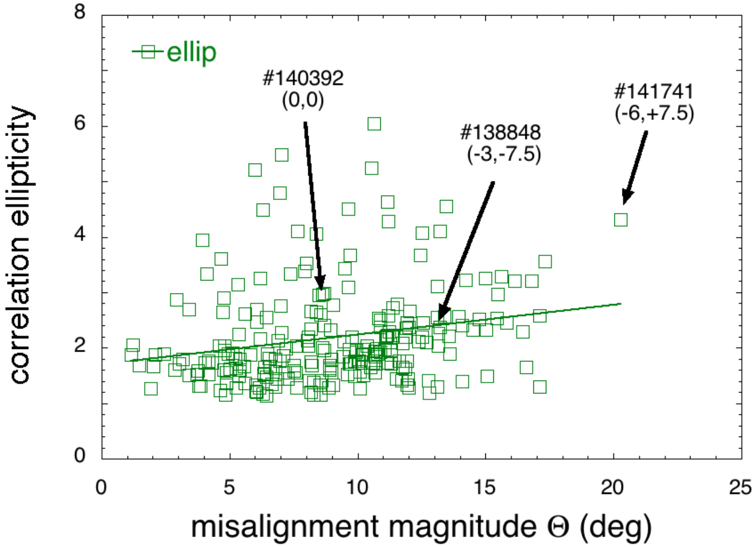
Correlation vs. B Field Misalignment

- Correlation tilt direction near B direction for large misalignments
- Ellipticity increase from ε = 2 to 3 with increasing misalignment
- Misalignment seems to affect 2-D correlation for Φ > 15º (or so)

difference of tilt and B field vs. Φ



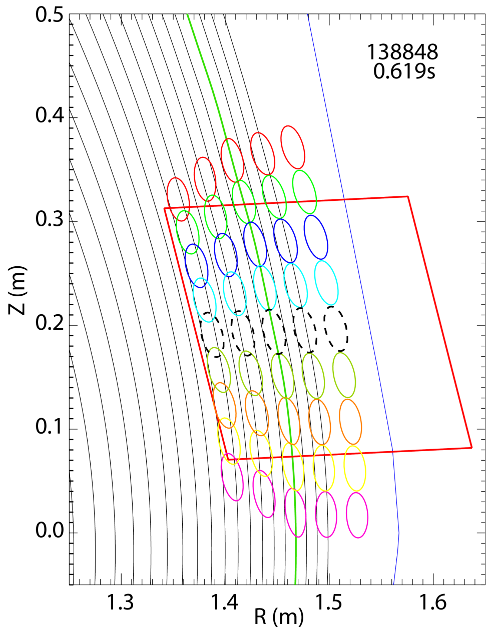
correlation ellipticity vs. Φ



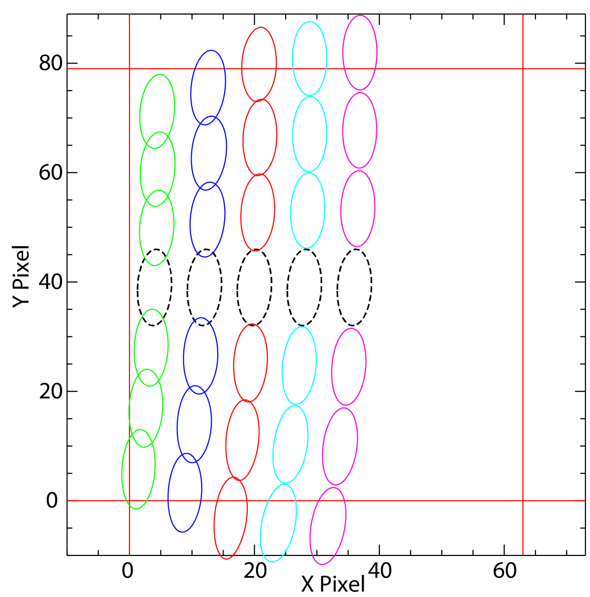
Magnetic Field Tilting of Flux Tubes

- Magnetic flux tubes change their tilt over GPI image due to flux surface curvature and magnetic shearing
- Magnetic field tilt change over ±7.5 cm poloidally is ~ -6º to +7º much less than observed correlation tilt change -36º to 145º

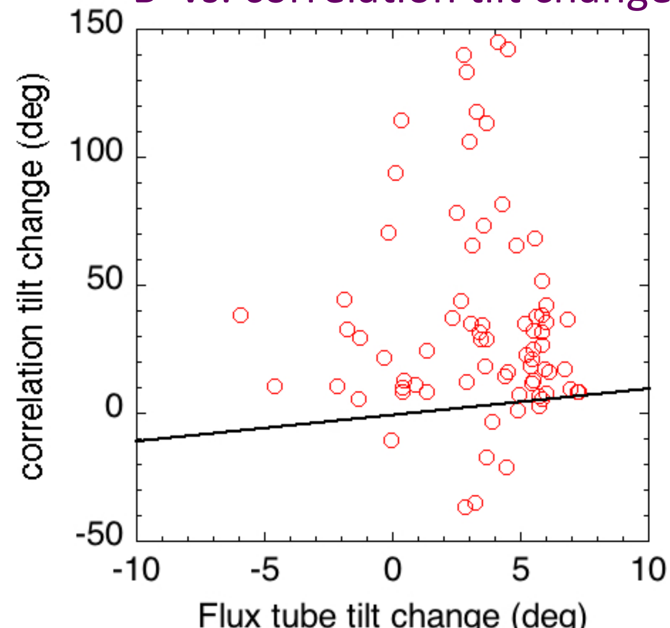
flux tubes in (R,z) plane



flux tubes in GPI plane

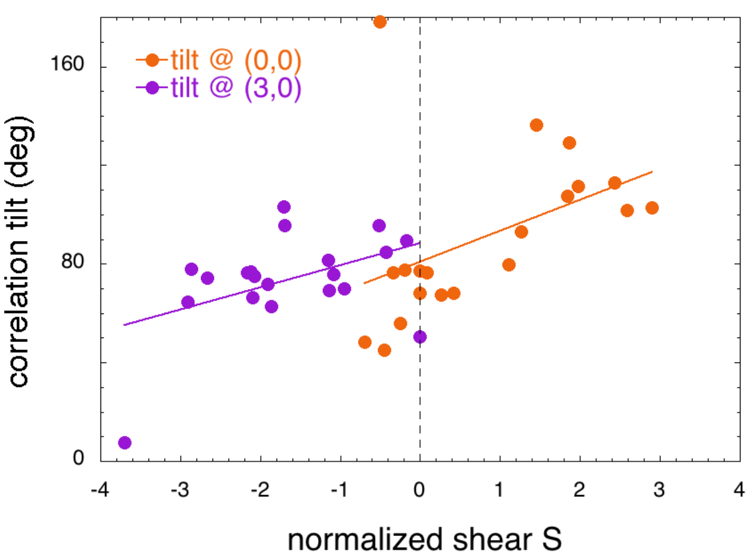


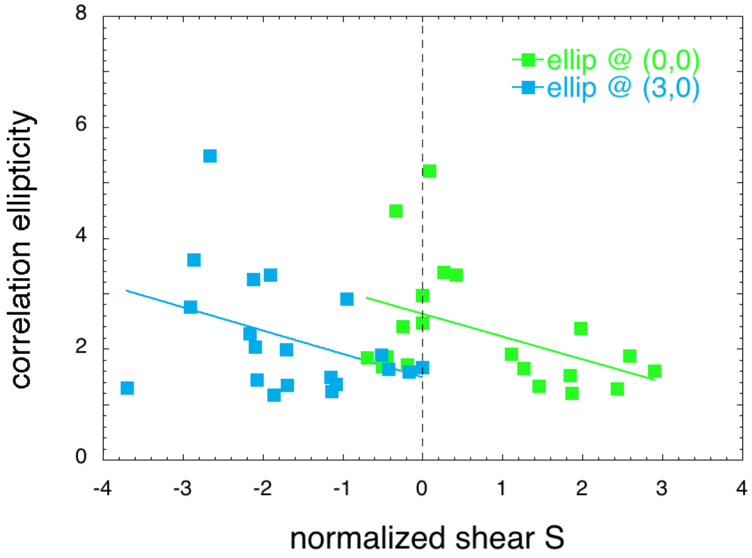
B vs. correlation tilt change



Poloidal Flow Shearing of Turbulence

- Normalized flow shear $S=(dV_{pol}/dr)(L_{rad}/L_{pol})\tau_{auto}$ evaluated for this 20 shot database for (r,p) = (0,0) and (3,0) grid points
- See no consistent changes of correlation tilt or ellipticity with |S|, but in theory these may depend on the sign of S

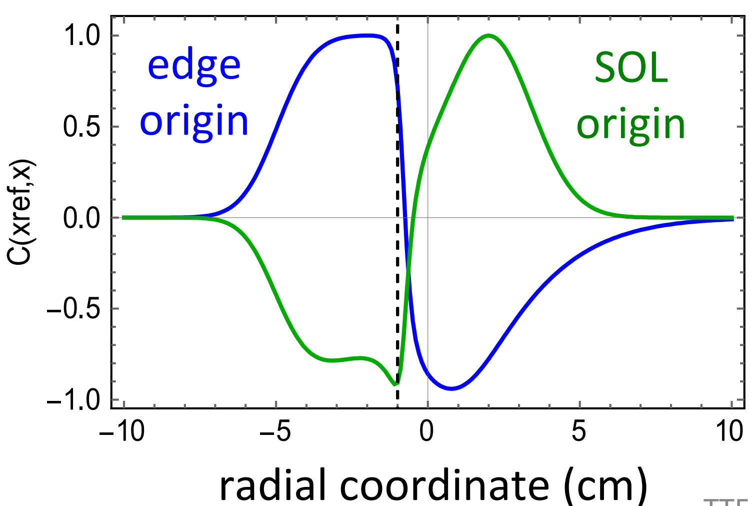




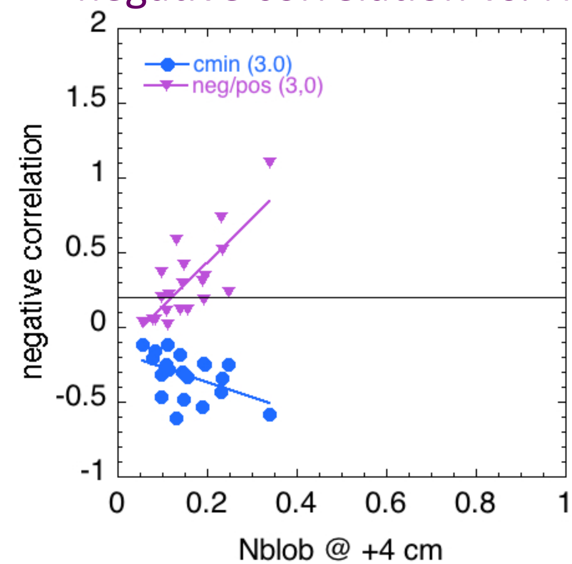
Blob vs. Negative Hole Correlations

- Holes (negative density perturbations) are expected theoretically to correlate with blobs, but to move inward (not outward)
- Simple 1-D model for blob-hole pairs shows dipole-like radial correlation functions, similar to some measured correlations
- Some increase in negative correlations with Nblob @ + 4 cm

1-D blob-hole correlation



negative correlation vs. Nblob



Neutral Shadowing Effect in GPI ?

- Depletion of neutral density by blobs might cause correlated negative regions of GPI emission (Stotler JNM ‘03, Marandet JNM ‘13), similarly to BES (Moulton, NF ‘15)

- To be significant, neutral MFP < turbulence size, which occurs in NSTX near peak emission (r = -2 cm) and farther inward

- However, D neutrals in NSTX GPI are not highly directional, due to molecular dissociation and wall recycling of D_2

=> so far no clear evidence of shadowing from GPI results or simulations, but no definitive conclusions can be drawn without further analysis

Summary of 2-D Correlation Results

- From elliptical fits to positive correlation function and search for negative correlation regions over 5x3 grid in image:
  - average ellipticity $\varepsilon = 2.2 \pm 0.9$ (standard deviation)
  - average tilt angle $\varphi = 87 \pm 34º$ (poloidal direction is 90º)
  - minimum negative correlation cmin = -0.30 ± 0.15
  - total ratio of correlations neg/pos = 0.25 ± 0.25
- Largest negative correlations cluster ~ 5-10 cm inside/above and outside/below origin point of correlation functions
- Radial correlation functions often have dipole-like shape, but poloidal correlation functions usually Gaussian-like

Interpretation of 2-D Correlation Results

- Correlation tilt angle is affected by local B field misalignment, but only above large misalignments $\Phi > 15^{\circ}$ (or so)
- Magnetic field shearing of edge flux tubes
- Poloidal flow shearing of turbulence does not significantly affect correlation functions in this database, even with $S > 1$
- Blob vs. hole correlations might be causing some of the negative correlation regions
- Neutral shadowing does not appear to be a significant effect

Remaining variations of 2-D correlation functions with plasma parameters are not yet understood

Directions for Further Research

- Analyze systematic scans of plasma parameters to help isolate plasma parameter variations of 2-D correlation functions
- Analyze 2-D correlation patterns of individual blob events to look for correlated holes, e.g. using conditional averaging
- Measure GPI cloud length along B to evaluate smearing effect
- Compare 2-D correlations directly with synthetic GPI diagnostic in XGC1 simulations, and use DEGAS 2 + XCG1 to evaluate the neutral density shadowing effect