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Variations in Edge and SOL Turbulence in NSTX

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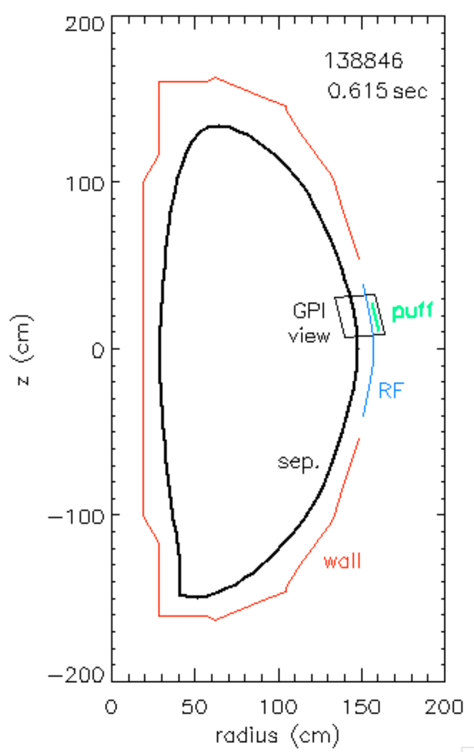
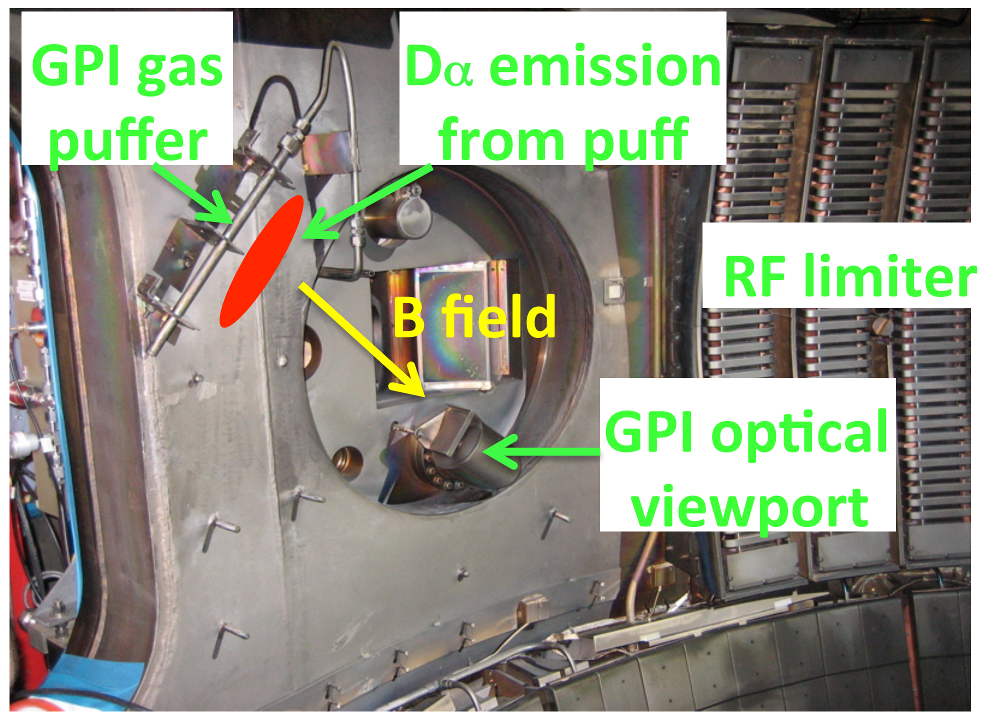
Abstract

Variations in edge and SOL turbulence were studied using a 140 shot database from the NSTX gas puff imaging (GPI) diagnostic. Analyses of the turbulence structure and motion was done using both cross-correlation and blob-tracking techniques. The relative fluctuation levels and blob formation rates were lower near and inside the separatrix for H-mode plasmas compared to Ohmic and L-mode plasmas, but similar in the far SOL. Poloidal correlation and blob lengths were roughly the same as radial turbulence correlation and blob lengths, and roughly independent of confinement regime. The radial turbulence velocity was outward in all cases, but the poloidal velocity reversed direction inside the separatrix for Ohmic and low-power L-mode plasmas. Variations of the turbulence quantities with global and local edge parameters will be described in detail. An attempt will be made to identify the basic mechanisms of the turbulence based on these variations and to evaluate the scaling of turbulent transport in the edge and SOL.

Gas Puff Imaging (GPI) Diagnostic on NSTX

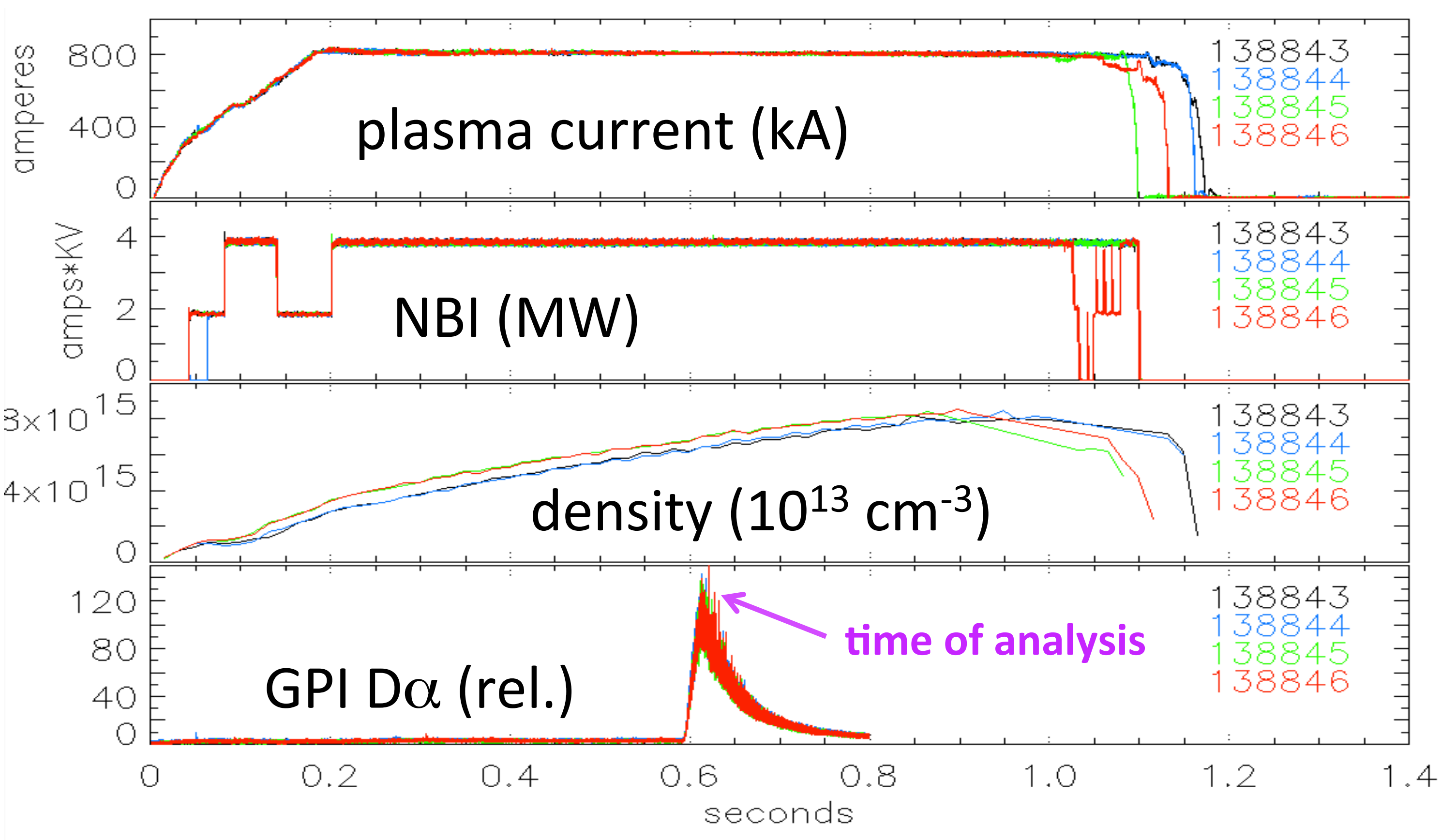
- D_2 gas puffed from GPI manifold on outer wall above midplane
- Dα light emission from gas puff viewed from along local B field
- Fluctuations in Dα light emission interpreted as edge turbulence





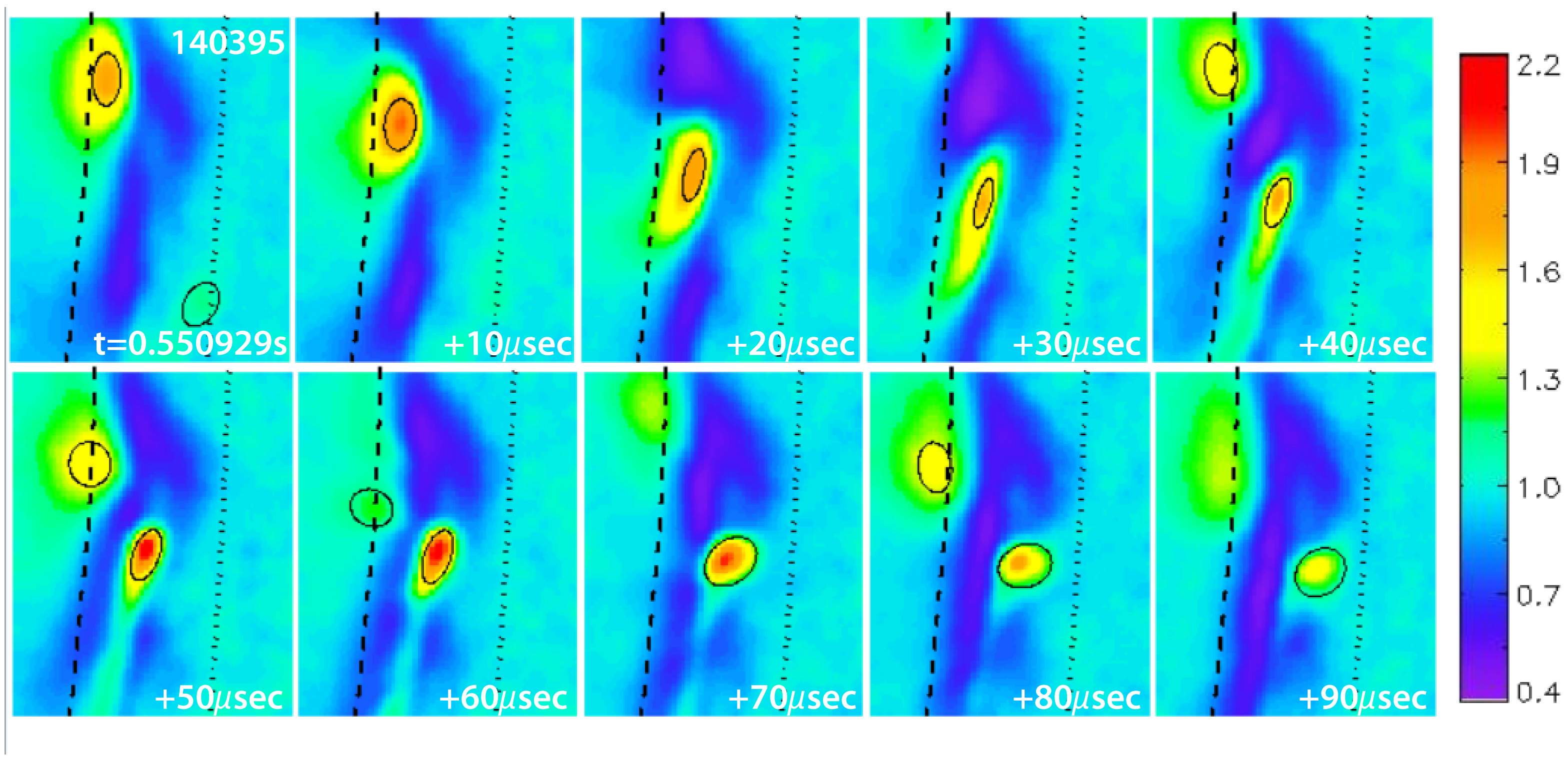
Time Dependence of GPI Signals

- GPI gas puffed once during shot and seen by local Dα emission
- Time of analysis for this database is ±5 msec around GPI peak



Typical Camera Images from GPI in NSTX

- Image data first normalized by average of images over 1 msec
- Positive excursions ≥ 1.5 normalized signal are tracked as blobs



Selection of Shots for the GPI Database

- Taken from 17 different XPs in 2010, H-mode, Ohmic, and L-mode
- All diverted deuterium plasmas, almost all (93%) lower-single-null
- Time of interest during steady-state with no transient events, i.e. *no large ELMs, MHD, power variations, or L-H transitions*
- B field line angle suitable for GPI (i.e. I_p/B_t = 0.2±0.05 MA/kG)
- GPI data taken at fastest possible rate of 400,000 frames/sec
- Outer midplane separatrix at least 3 cm inside GPI field of view

NSTX GPI Database from 2010 Run

Overall database

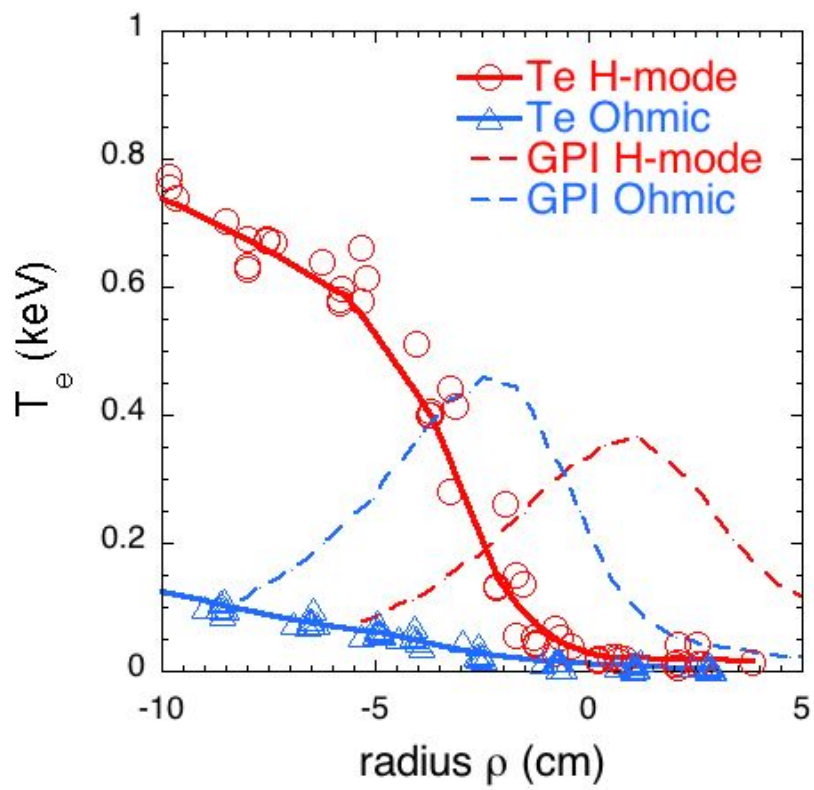
Number of shots	140
H-mode	93
Ohmic	33
L-mode	14
Plasma current:	I_p=0.65-1.15 MA
Toroidal field:	B_t=3.5-5.5 kG
safety factor:	q_{95} = 5.8-12.8
Elongation	k=1.8-2.5
Stored energy:	W_{mhd}=26-306 kJ
Average density:	n_e=1.3-7.0x10^{13} cm^{-3}
NBI heating:	P_{nb} = 0-6 MW
RF heating:	P_{rf} = 0-1.4 MW
Outer gap:	2.8-15.7 cm
Lithium:	0-370 mg/shot

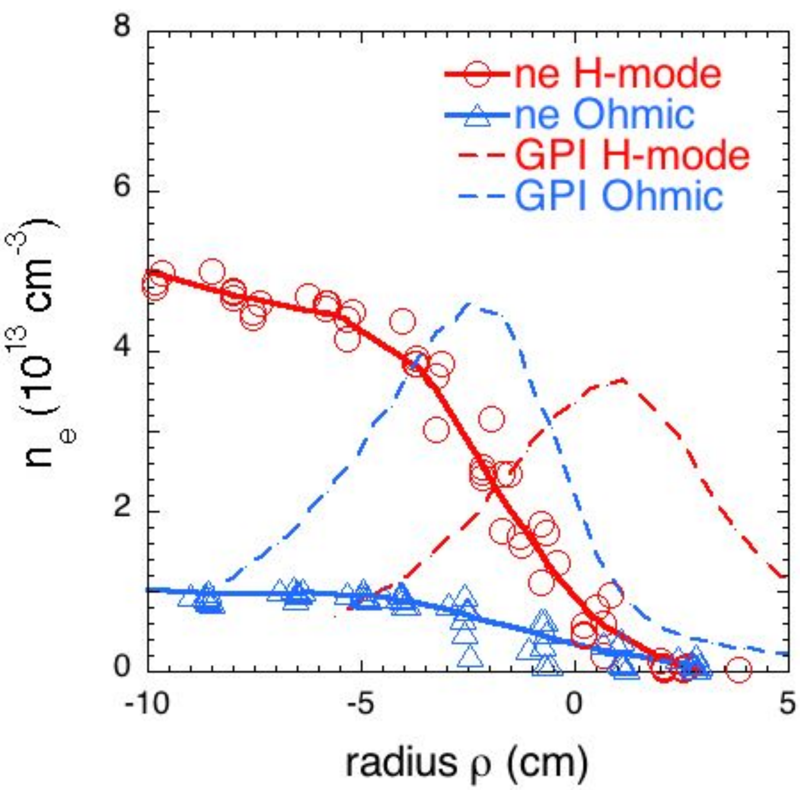
Sample plasmas used for profiles

	H-mode	Ohmic
shot range	140389-395	141746-756
time (sec)	0.532	0.215
I_p (kA)	830	830
B_t (kG)	4.9	3.6
W_{mhd} (kJ)	220	32
n_e (10^{13} cm^{-3})	5.2	1.6
P_{nb} (MW)	4.0	0
T_e(0) (eV)	920	530
n_e(0) (10^{13} cm^{-3})	5.6	2.3
T_e(a) (eV)	29±17	13±6
n_e(a) (10^{13} cm^{-3})	0.92±0.54	0.37±0.23
T_e @ -2 cm (eV)	134±53	23±4
n_e @ -2 cm (/10^{13})	2.1±0.47	0.47±0.17

Sample Edge Profiles in NSTX

- Te and ne profiles from Thomson scattering (7 shots each)
- GPI profiles from average Dα over time near peak time

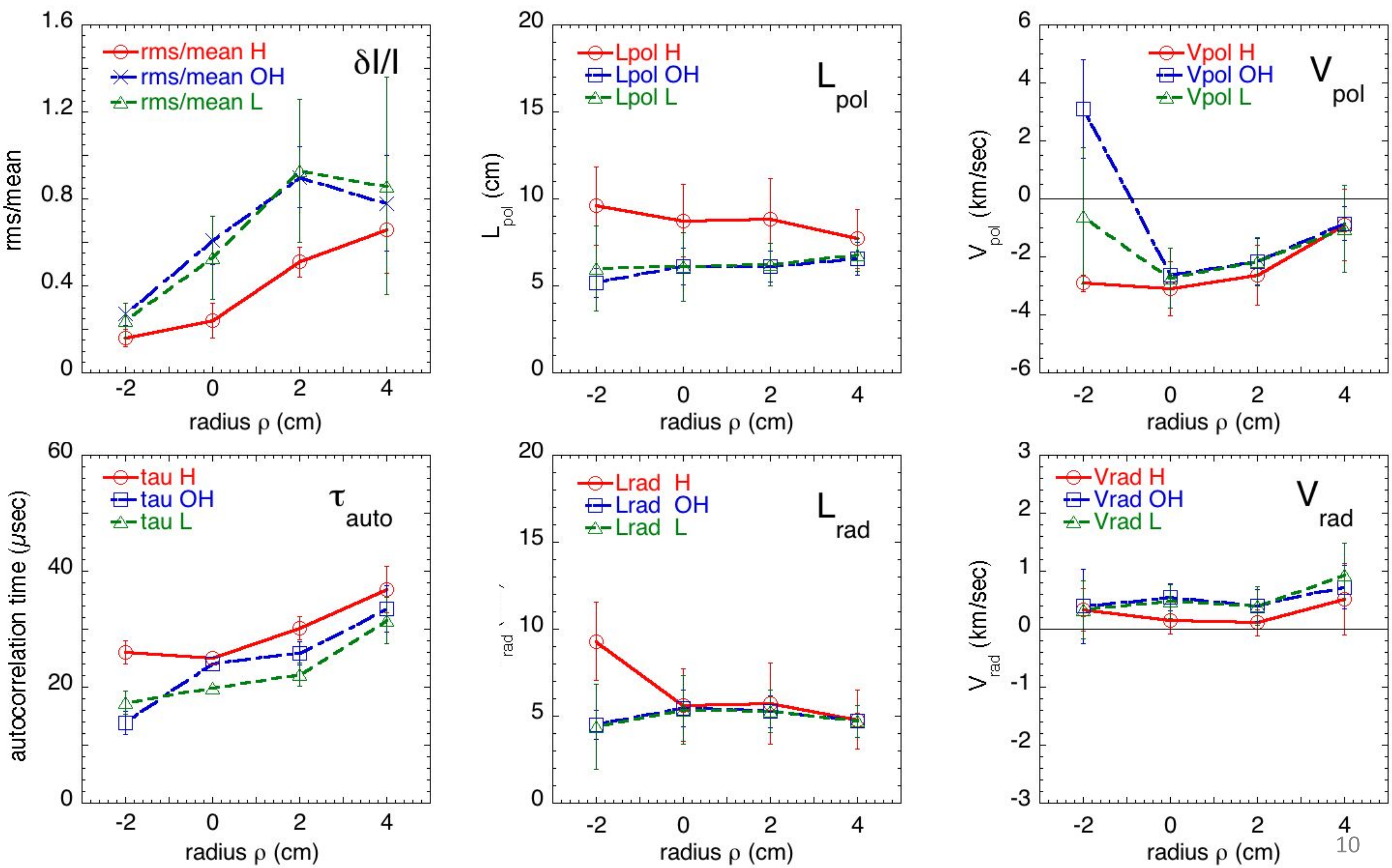




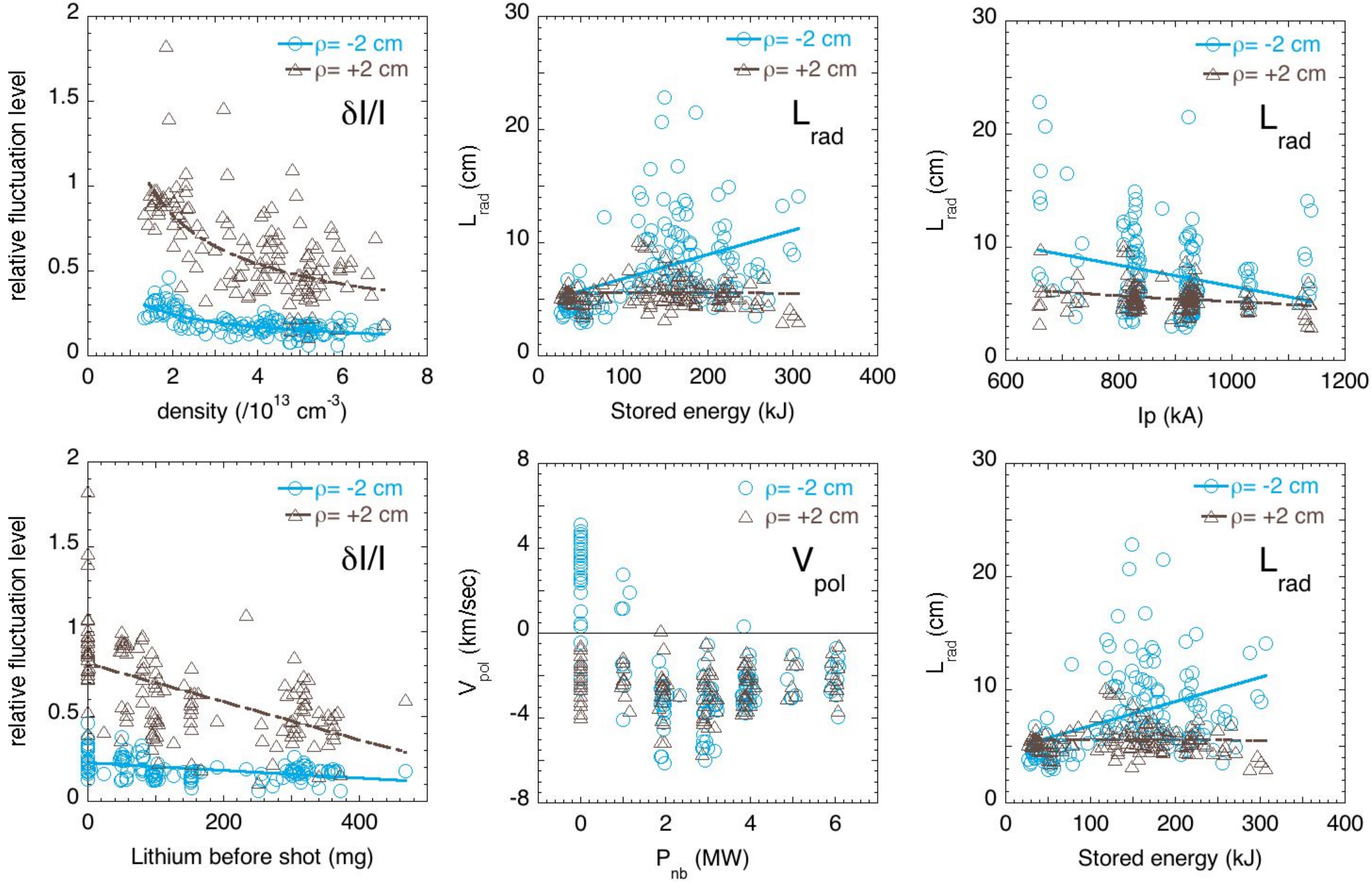
Turbulence and Blob Data Analysis

- Image data first normalized by average of images over ≥ 1 msec
- **Turbulence analysis** uses standard cross-correlation methods, averaging results over ±5 msec around peak of GPI signal
- **Blob analysis** tracks structures with height ≥ 1.5 x average height at that spatial position, averaging over ±5 msec as above
- Results binned near -2 cm, 0 cm, +2 cm, +4 cm from separatrix
- Sometimes shots are segregated into H-mode, Ohmic, L-mode

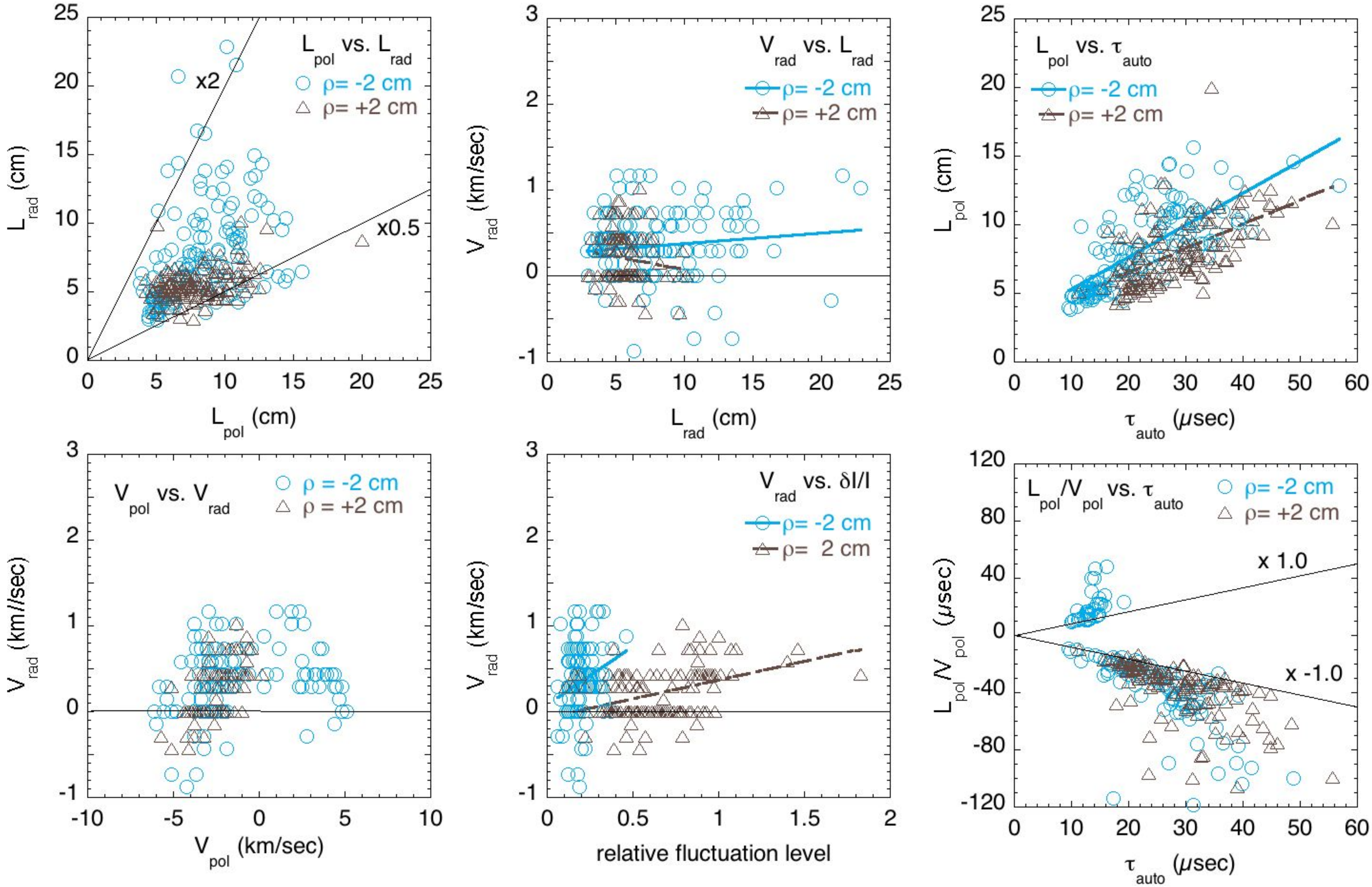
Radial Profiles of Turbulence



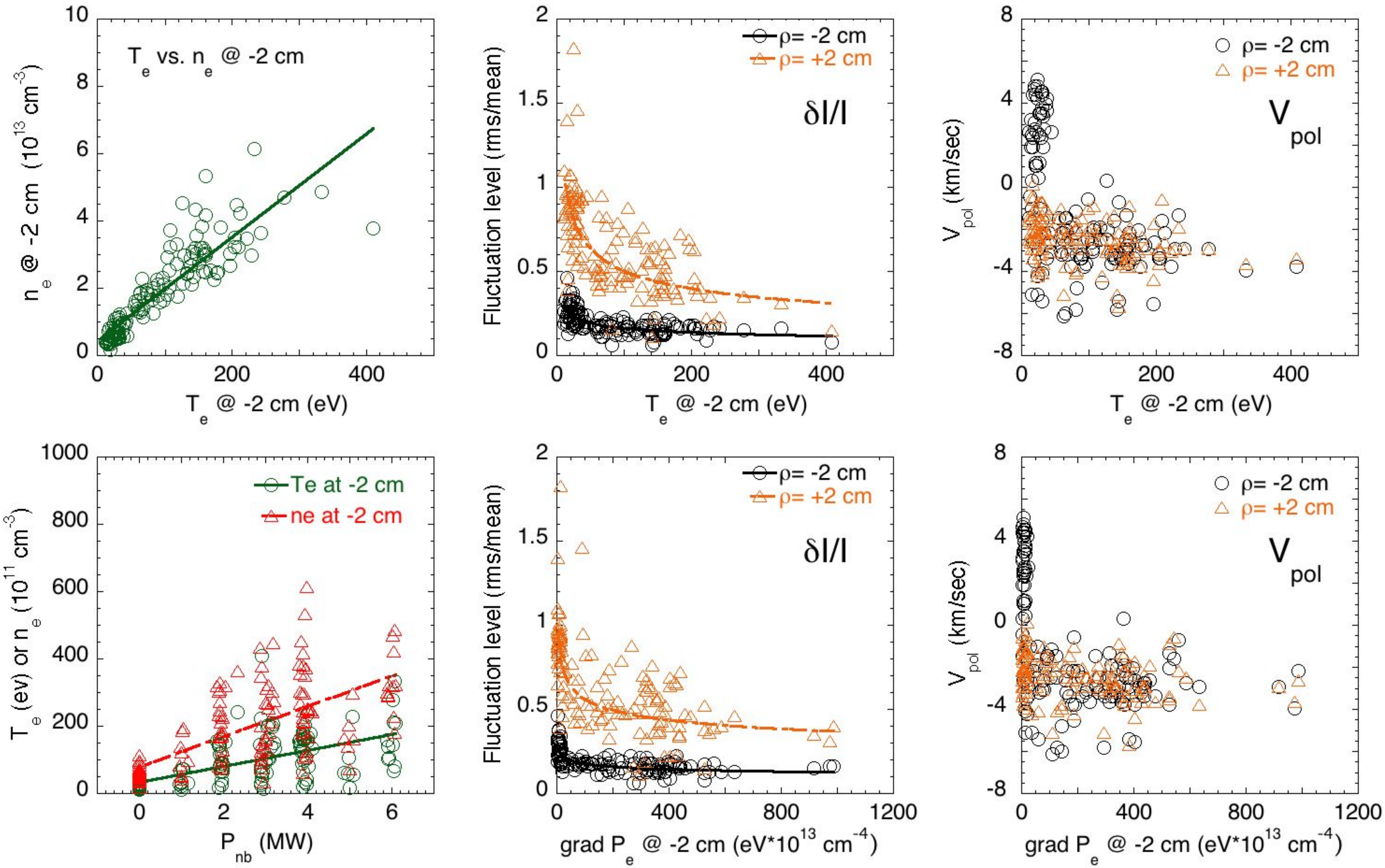
Variation with Global Parameters



Turbulence Inter-Relationships

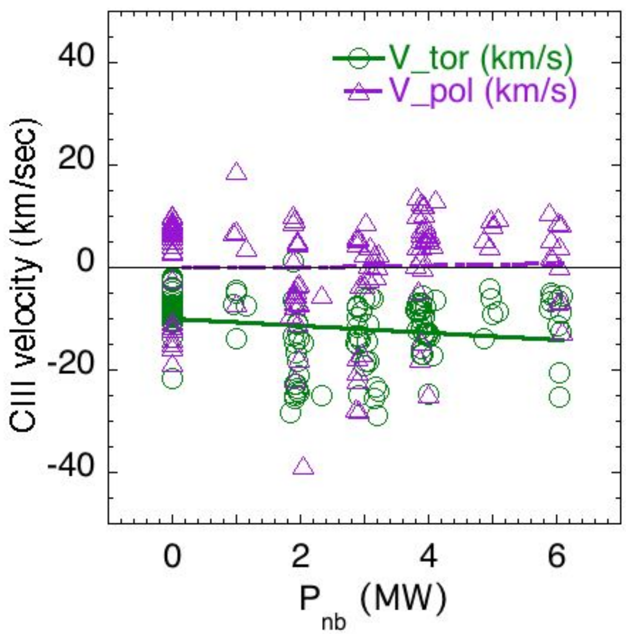


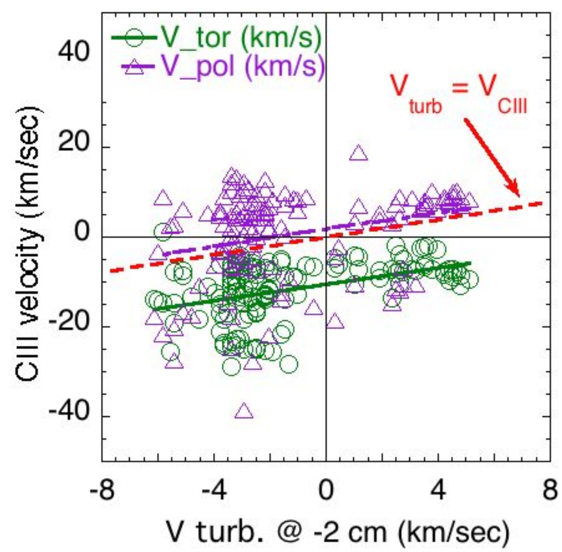
Variation with Edge Parameters



Turbulence Velocity vs. Carbon Ion Velocity

- Edge velocities measured by CIII line ~ 2-3 cm inside separatrix in lab frame using Edge Rotation Diagnostic (R. Bell)
- Surprisingly little correlation of CIII velocities and NB power
- Some correlation (0.28) between turbulence V_{pol} and CIII V_{pol}



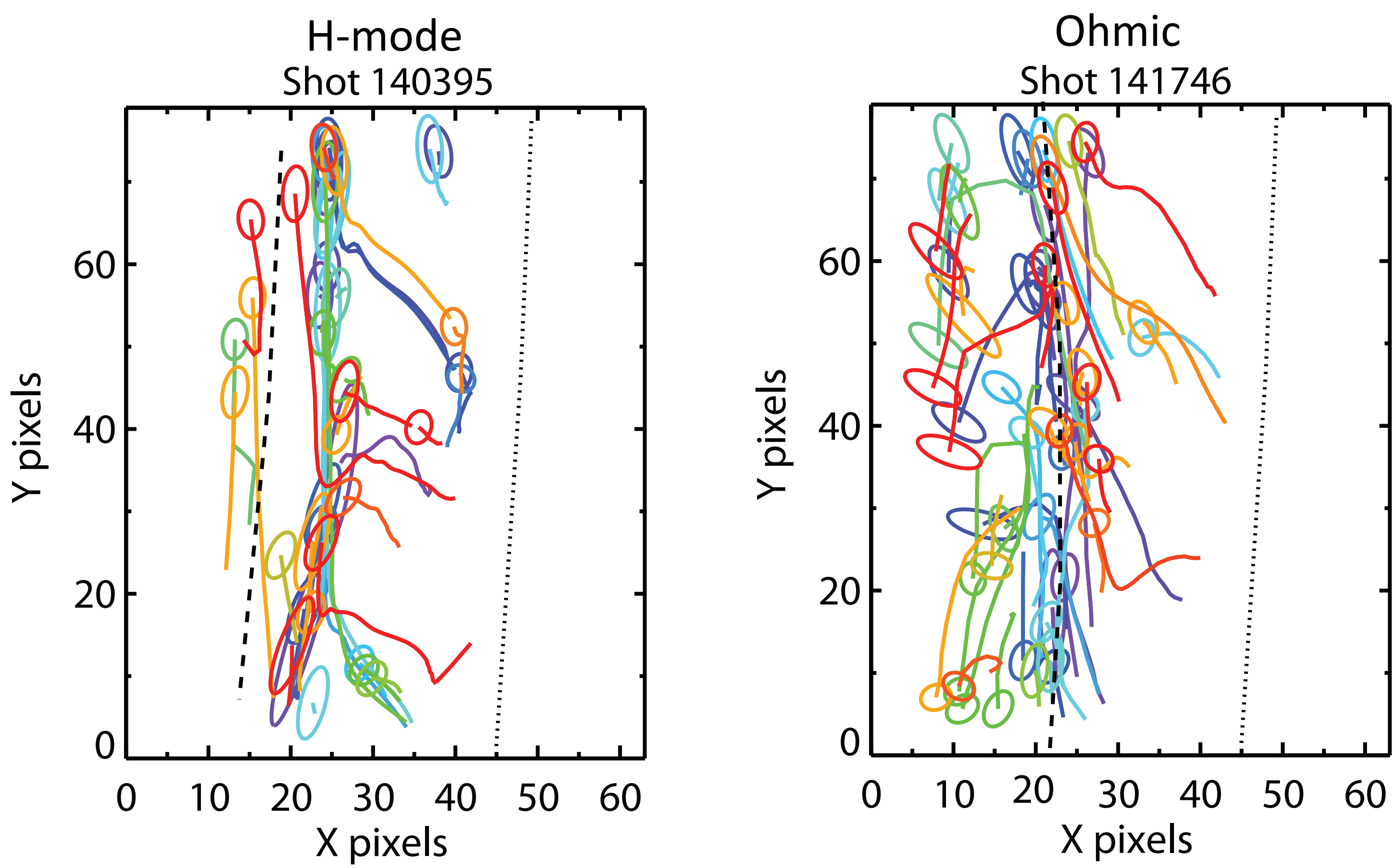


Summary of Turbulence Correlation Results

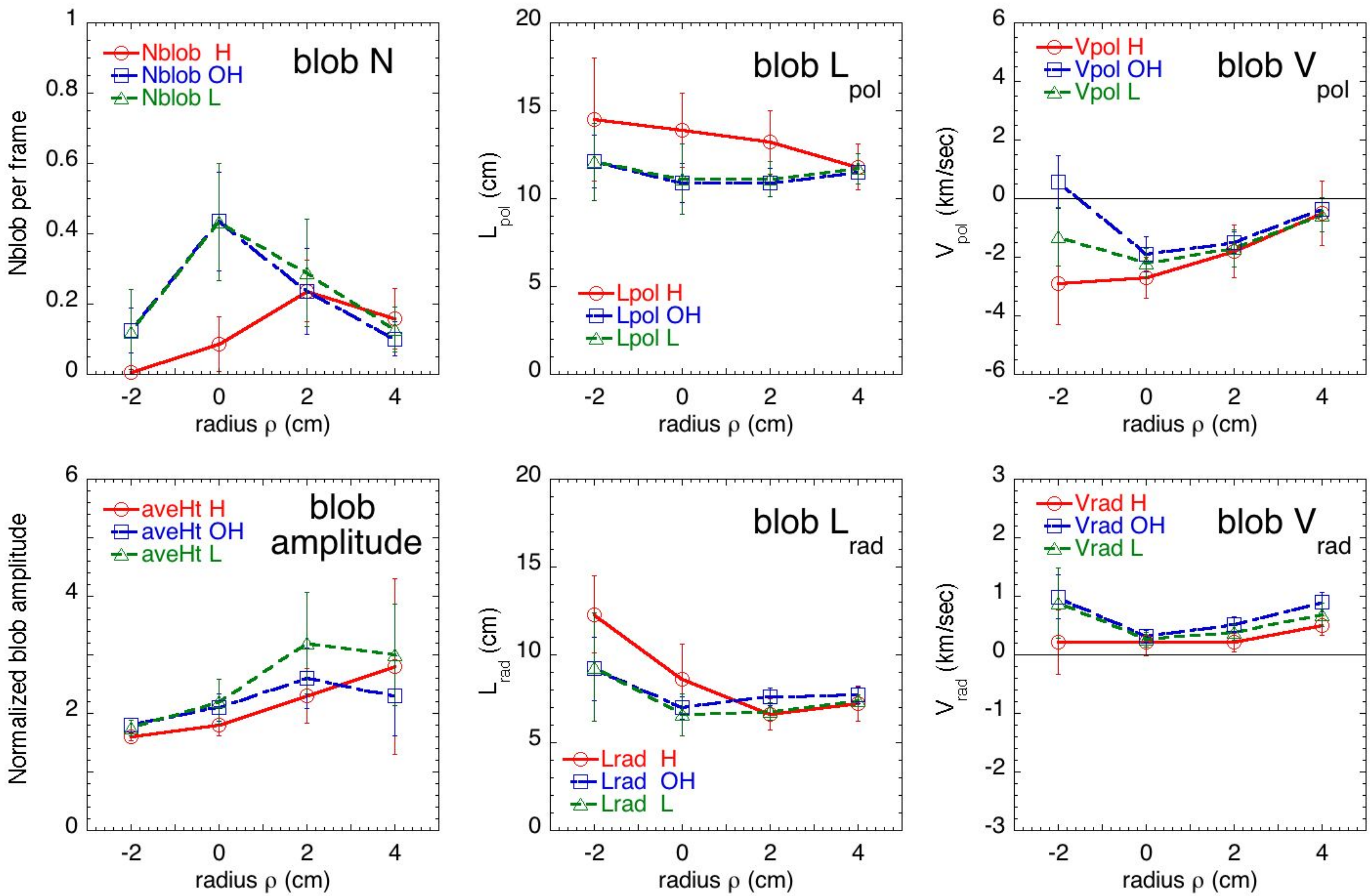
- Fluctuation levels decrease with increasing line-averaged density, P_{nb}, W, lithium, and with increased edge T_e and grad T_e, all roughly corresponding to changes from OH to L to H-mode
- Correlation times and correlation lengths are roughly similar for all shots, but some increase in L_{rad} inside separatrix with W
- Poloidal correlation velocity reverses direction inside separatrix in Ohmic shots, but largely constant in all other cases
- Radial correlation velocity roughly similar for all radii and shots
- Some correlation (0.28) between turbulence V_{pol} and CIII V_{pol}

Sample Blob Tracking Results

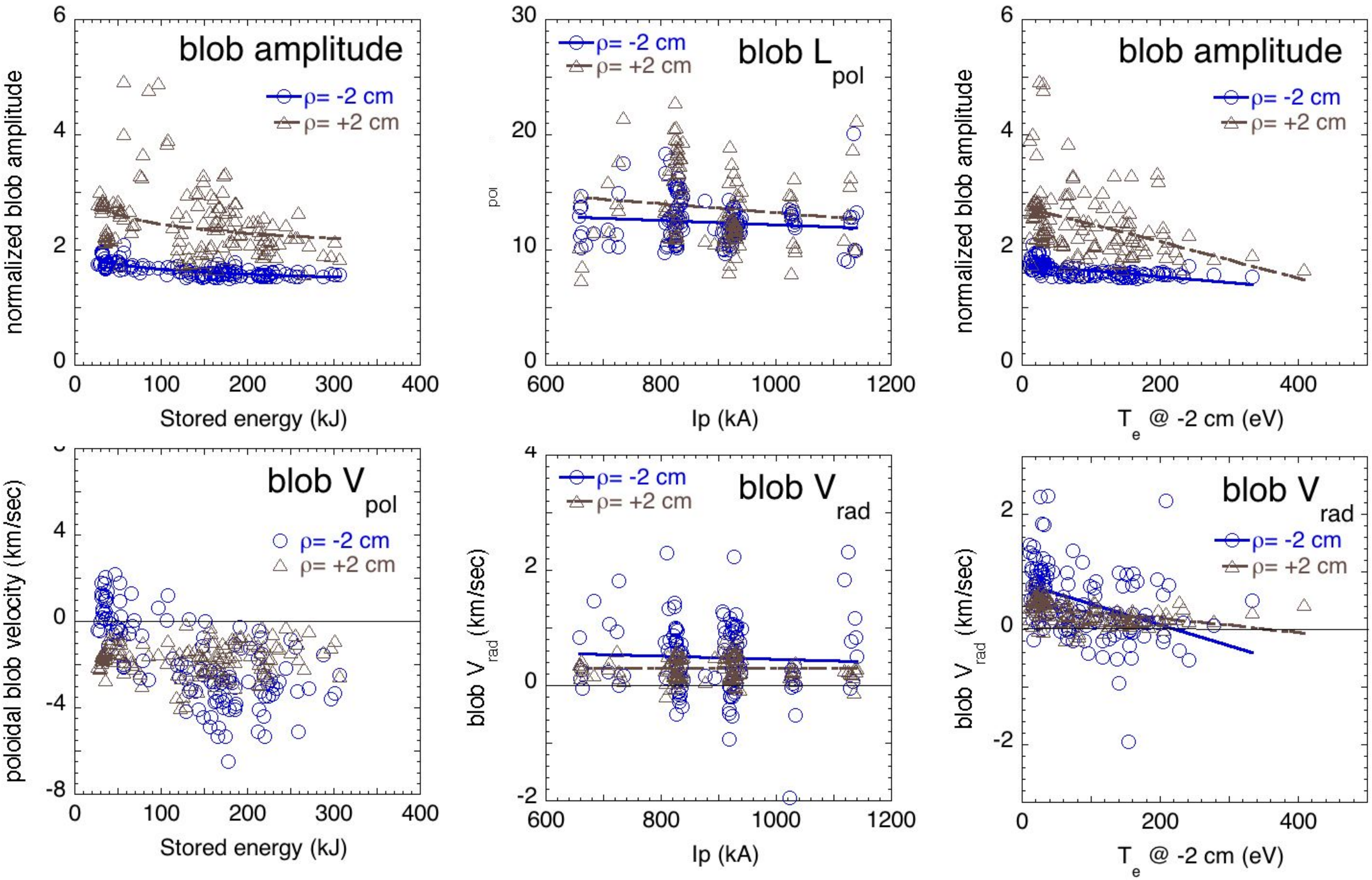
- Blob tracking done for structures with normalized height ≥ 1.5
- Sample blobs in 2 msec of H-mode (left) and Ohmic (right) shots



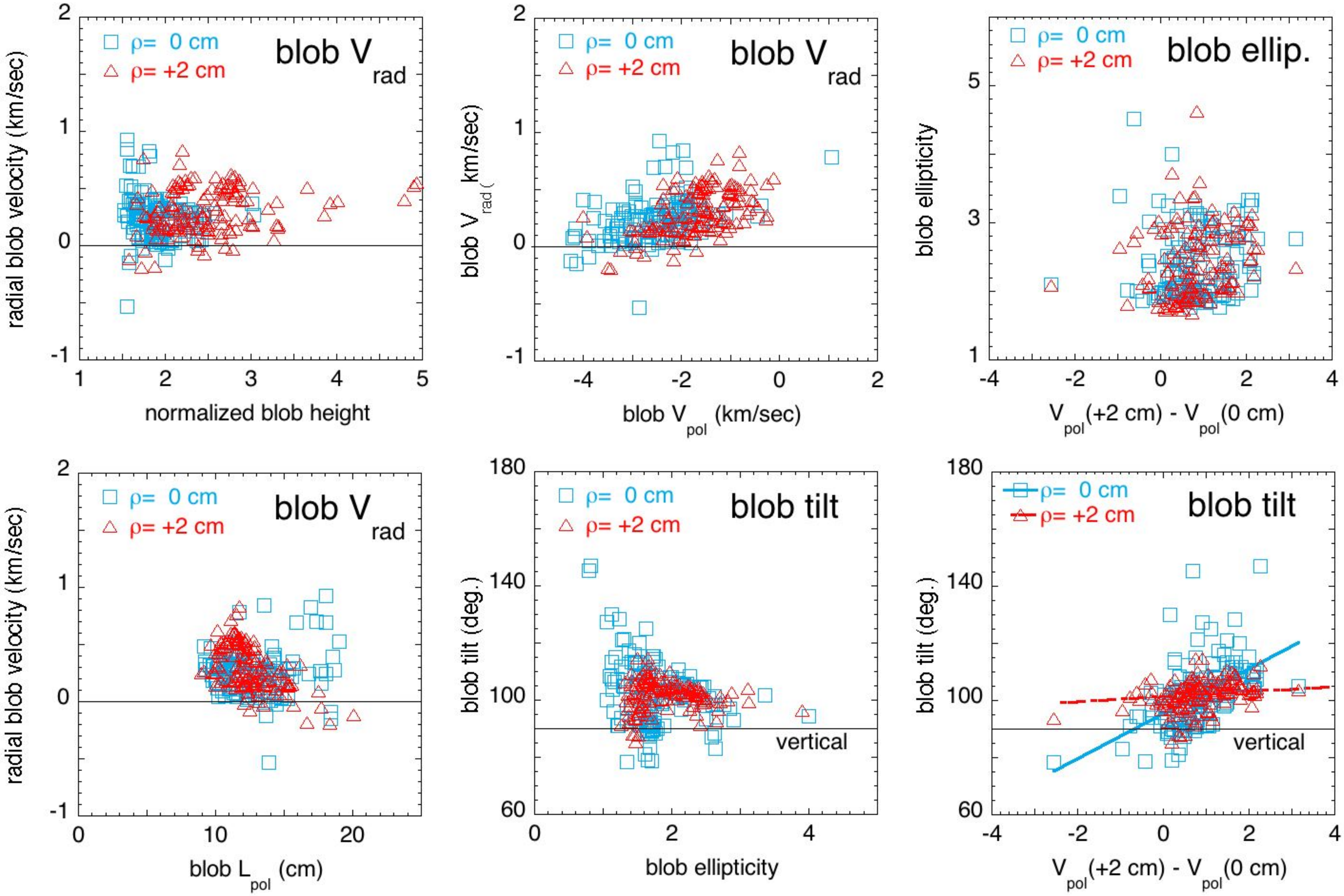
Radial Profile of Blob Results



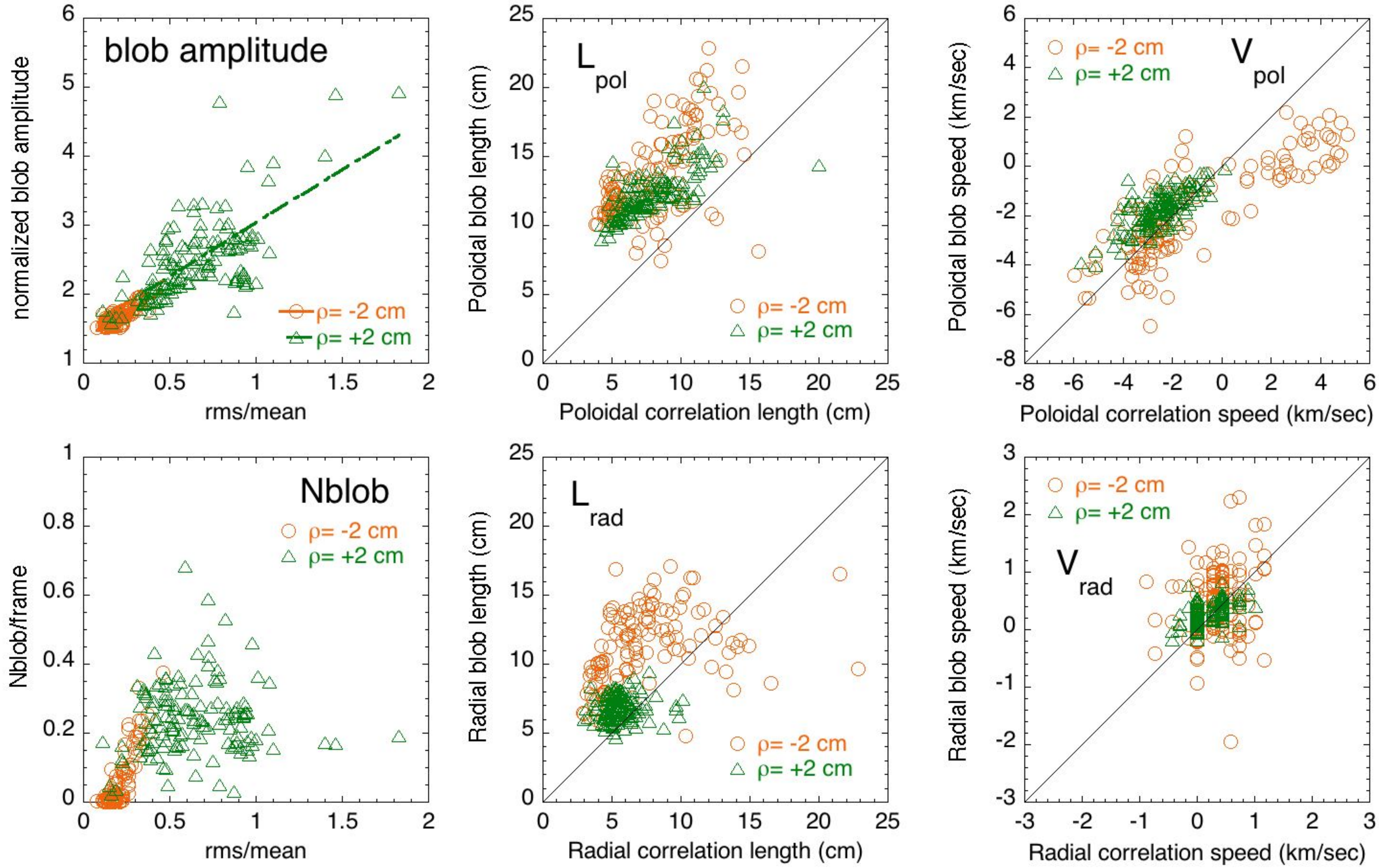
Blob Variations with Plasma Parmeters



Blob-Blob Inter-relationships



Blobs vs. Turbulence Correlations



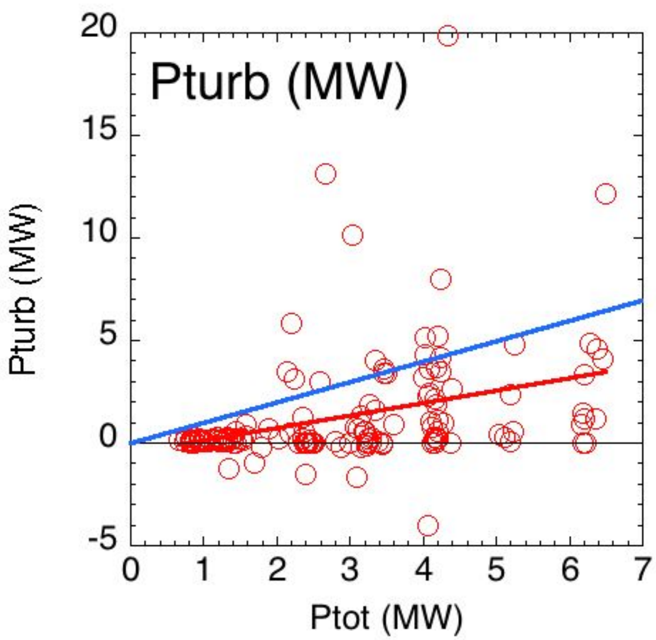
Summary of Blob Tracking Results

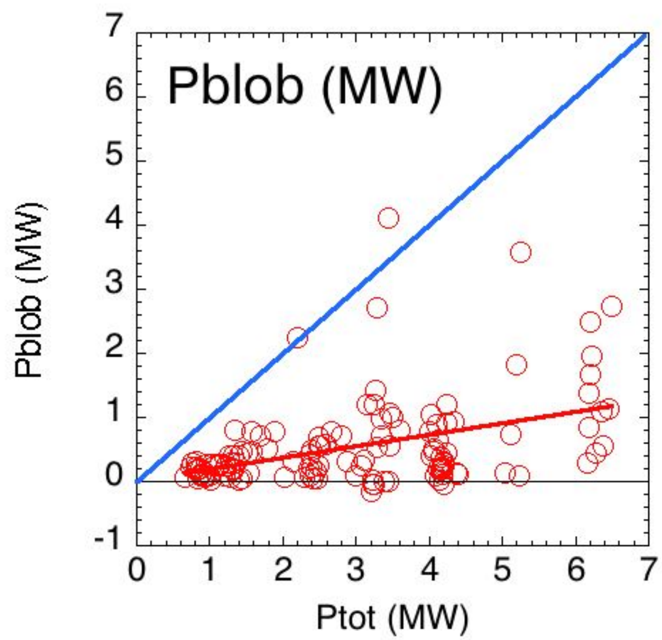
- Number of blobs near and inside separatrix significantly smaller in H-mode than L-mode or Ohmic shots
- Average blob height increases with radius and decreases with increased line-averaged density, Pnb, and edge Te
- Blob correlation lengths are roughly similar for all shots
- Blob poloidal velocity reverses direction inside separatrix in Ohmic shots, but largely constant in all other cases
- Blob radial velocity roughly similar for all radii and shots
- Blob properties similar to correlation properties over database

Turbulent and Blob Heat Transport

- Estimate turbulent transport from $Q = 5/2\langle\delta p\ \delta V_r\rangle$, so here $P_{turb} \sim 5\ nT_e\ (\delta I/I)\ V_r$ Area, at 2 cm inside separatrix

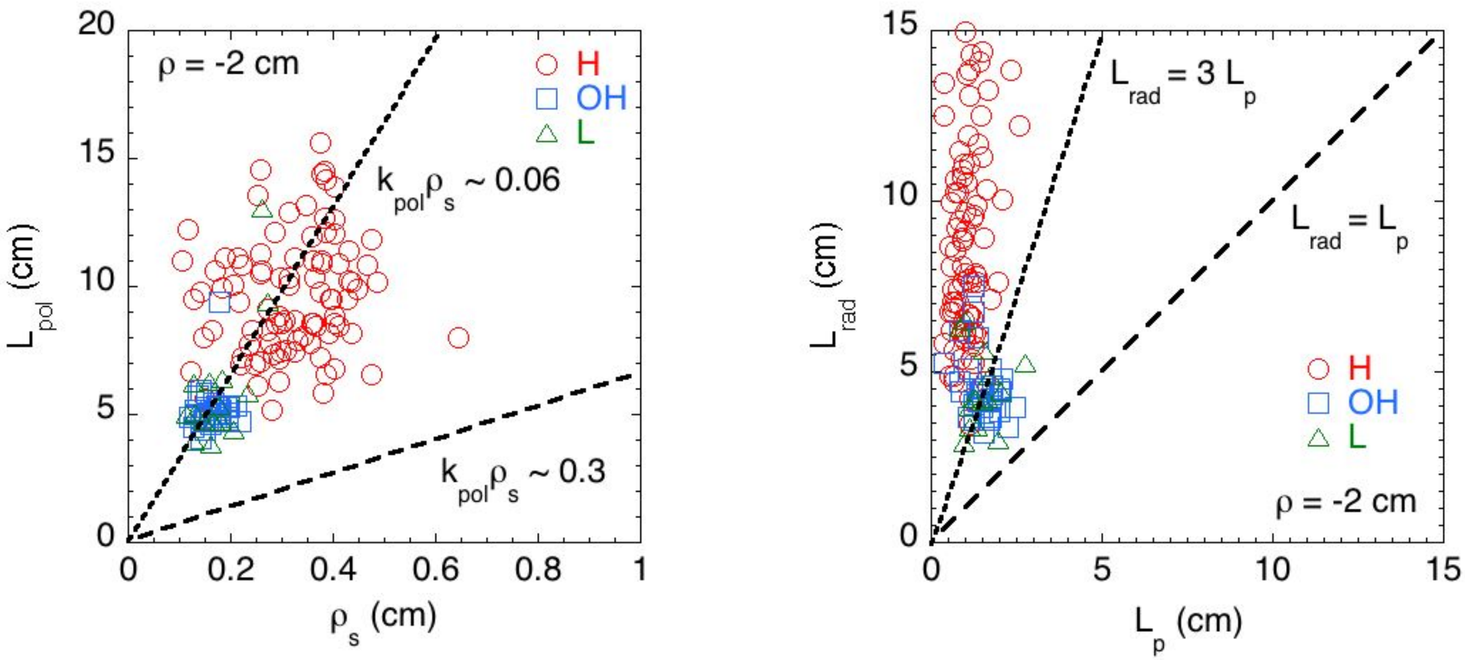
- Estimate blob transport as $P_{blob} \sim E_{blob} f_{blob}$, where E_{blob} is the energy/blob (~100 J) and f_{blob} is their frequency (~100 kHz)





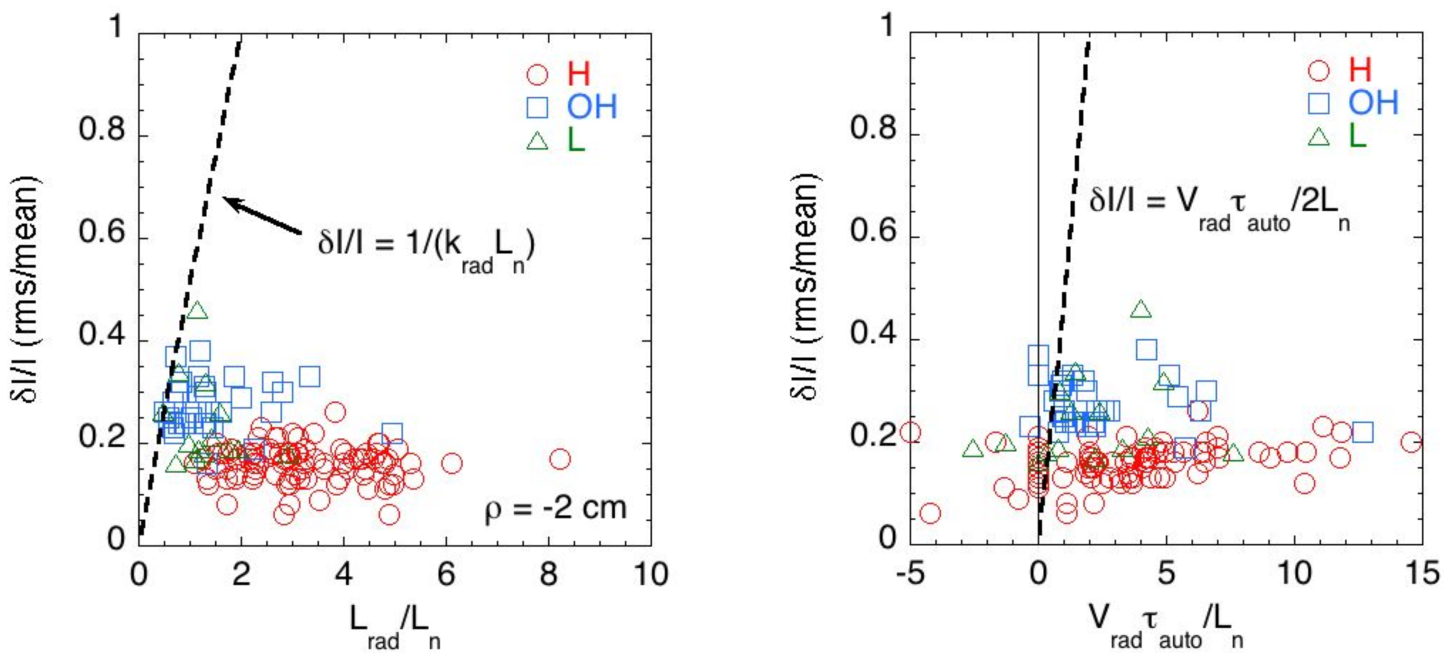
Physics of Turbulence Size Scale

- Drift wave turbulence models have typically $k_{pol}\,\rho_s \sim 0.3$
- Interchange turbulence typically has $L_{rad} \sim L_{p(ressure)}$
- Measured size scales are ~3-5 times larger than these



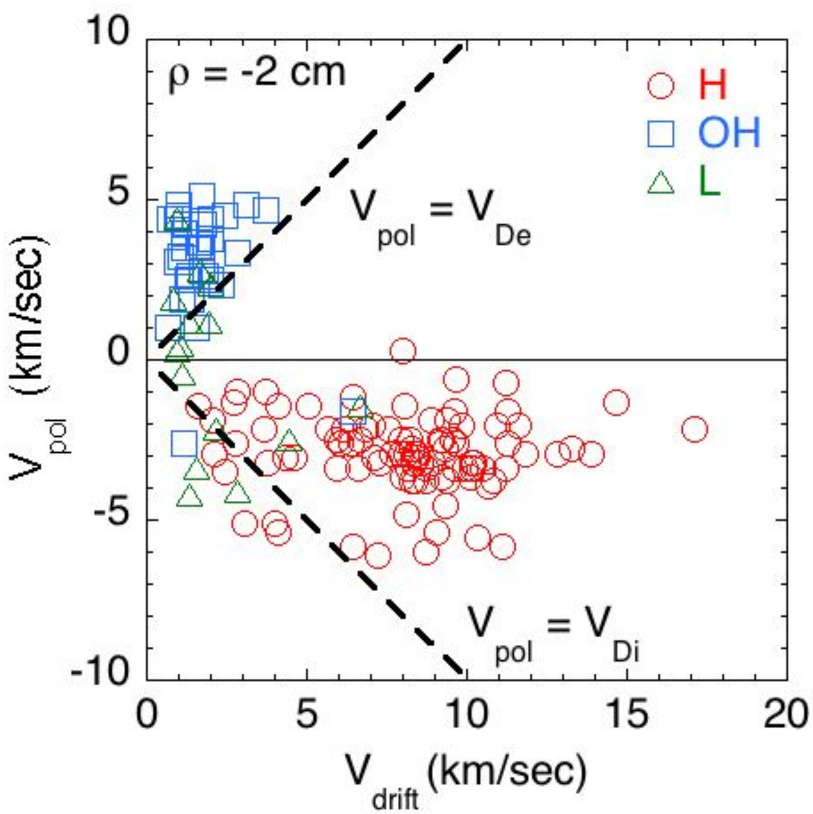
Physics of Turbulence Saturation

- Expect for saturation by wave breaking: $\delta n/n \sim 1/k_{rad}L_n$
- Expect for saturation of interchange modes: $\delta n/n \sim V_{rad}\omega/L_n$
- Assume $k_{rad} \sim 2/L_{rad}$, $\omega \sim 2/\tau_{auto}$, $\delta n/n \sim \delta I/I$ for GPI at ρ= -2 cm
- Measured $\delta I/I$ are below these limits, especially for H-mode



Physics of Poloidal Turbulence Velocity

- Expect drift waves have $V_{pol} = \pm V_{drift} = \pm c_s\rho_s/L_n$ in rest frame
- At ρ = -2 cm, V_{pol} (OH) is close to $V_{d,e}$, but V_{pol} (H) ~ (1/3) $V_{d,i}$



Ion V_{pol} in H-mode may be due to:

1) shift from e^- to i^+ drift waves

2) increased outward E_{rad}

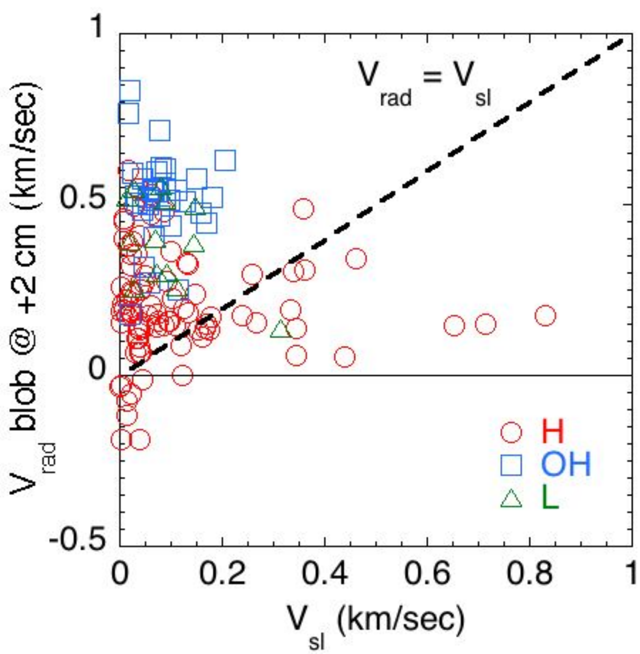
3) NBI-induced toroidal rotation

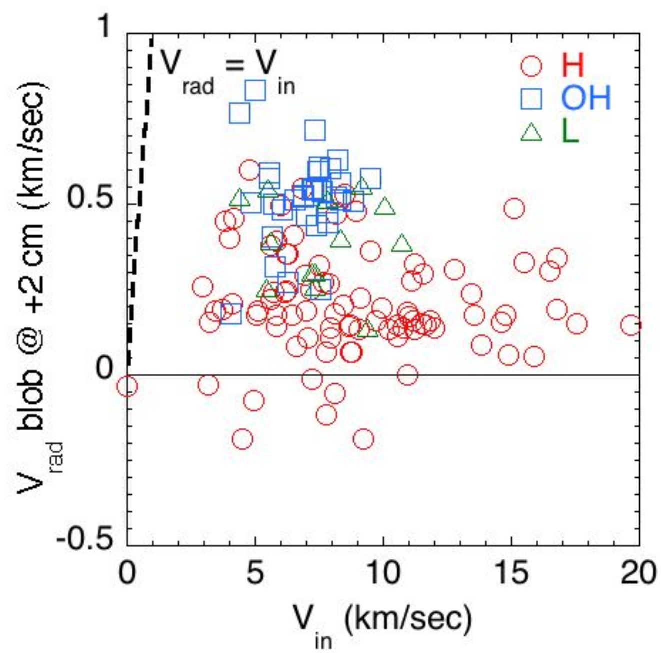
   V_{pol} (NBI) ~ (B_p/B_t) V_{tor}

   V_{pol} (NBI) ~ - 1-10 km/sec (?)

Physics of Radial Blob Velocity

- Sheath-limited radial blob velocity: $V_{sl} = c_s (L_{||}/R) (\rho_s/\delta_b)^2 (\delta n/n)$
- Inertial regime radial blob velocity: $V_{in} = c_s (\delta_b/R)^{1/2} (\delta n/n)^{1/2}$
- Assume T_e from ρ= 0 cm, $\delta_b \sim L_{pol}/2$, R=150 cm, $\delta n/n \sim \delta I/I$
- Measured blob V_{rad} @ ρ= +2 cm lies between V_{sl} and V_{in}





Summary of Physics Results

- Poloidal turbulence size scale L_{pol} from GPI at ρ = -2 cm is in between simple drift-wave and interchange scale lengths
- Saturation levels of turbulence $\delta I/I$ from GPI at ρ = -2 cm is lower than expected from simple theoretical estimates
- Poloidal speed of turbulence V_{pol} from GPI at ρ = -2 cm is about x3 lower than diamagnetic drift velocities
- Radial blob speed V_{rad} from GPI at ρ = +2 cm is in between estimates based on sheath limited and inertial range models

=> partial consistency with drift-wave and interchange estimates but no clear evidence of 'scaling' with these parameters

Overall Summary and Conclusions

- The edge turbulence at a give location has relatively little variation in fluctuation level $\delta I/I$, size scale L_{rad} and L_{pol}, and turbulence velocity V_{rad} and V_{pol} over this database

- Blob height, size and velocity are similar to average fluctuation properties derived from correlation analysis

- The clearest variations in edge turbulence were:
  - decrease in fluctuation level $\delta I/I$ from OH to H-mode
  - decrease in # blobs inside separatrix from OH to H-mode
  - increase in L_{pol} (by less than x 2) from OH to H-mode
  - change of V_{pol} direction inside separatrix from OH to H-mode

- Turbulence and blob characteristics generally similar to those expected from simplified analytical physics models