Variations in Edge and SOL Turbulence in NSTX

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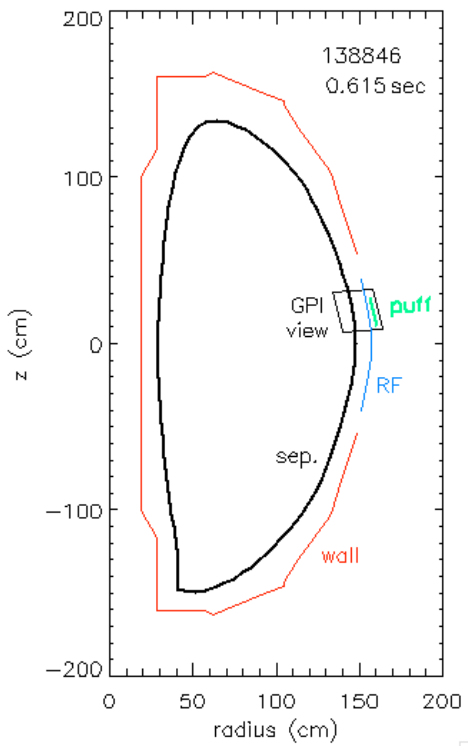
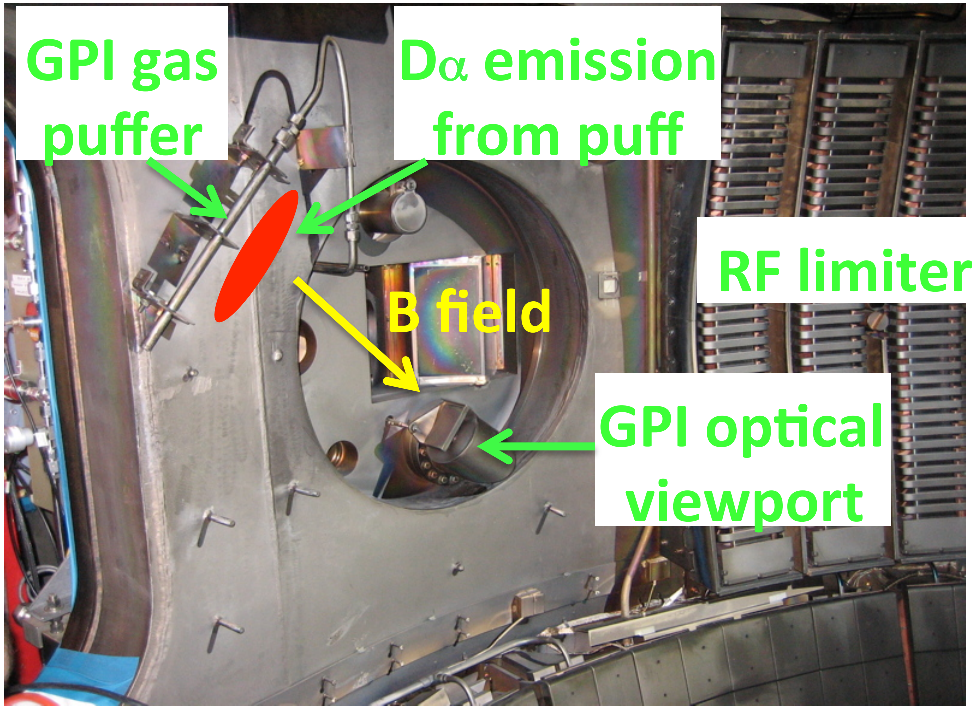
Abstract

This poster describes the range of variations in edge and SOL turbulence observed using a gas puff imaging (GPI) diagnostic in NSTX discharges. The database consists of 140 shots including Ohmic, L-mode, and H-mode plasmas measured during steady-state conditions (e.g. without ELMs). Turbulence quantities were evaluated using both cross-correlation analysis and blob tracking. Relative fluctuation levels varied from dI/I~15-100%, correlation times were t_{auto}~15-40 µsec, correlation lengths were L_{pol}~ L_{rad}~5-10 cm, and turbulence velocities were V_{pol}~2±1 km/sec and V_{rad}~0.5±0.5 km/sec outward. These variations were evaluated with respect to both the global and local edge plasma parameters, and compared with simplified theoretical models.

Gas Puff Imaging (GPI) Diagnostic on NSTX

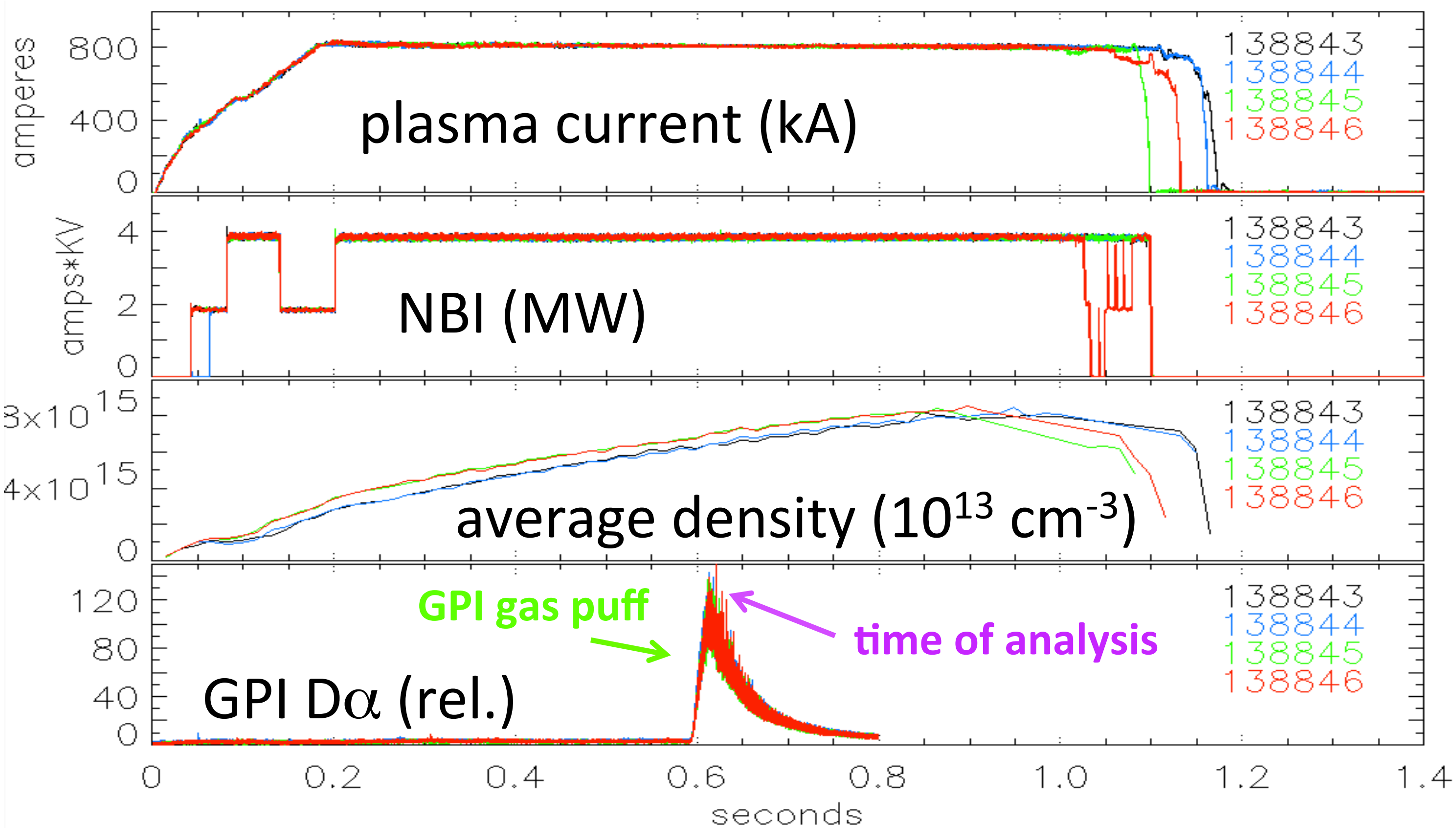
- D_2 gas puffed from GPI manifold on outer wall above midplane
- Dα light emission from gas puff viewed from along local B field
- Fluctuations in Dα light emission interpreted as edge turbulence





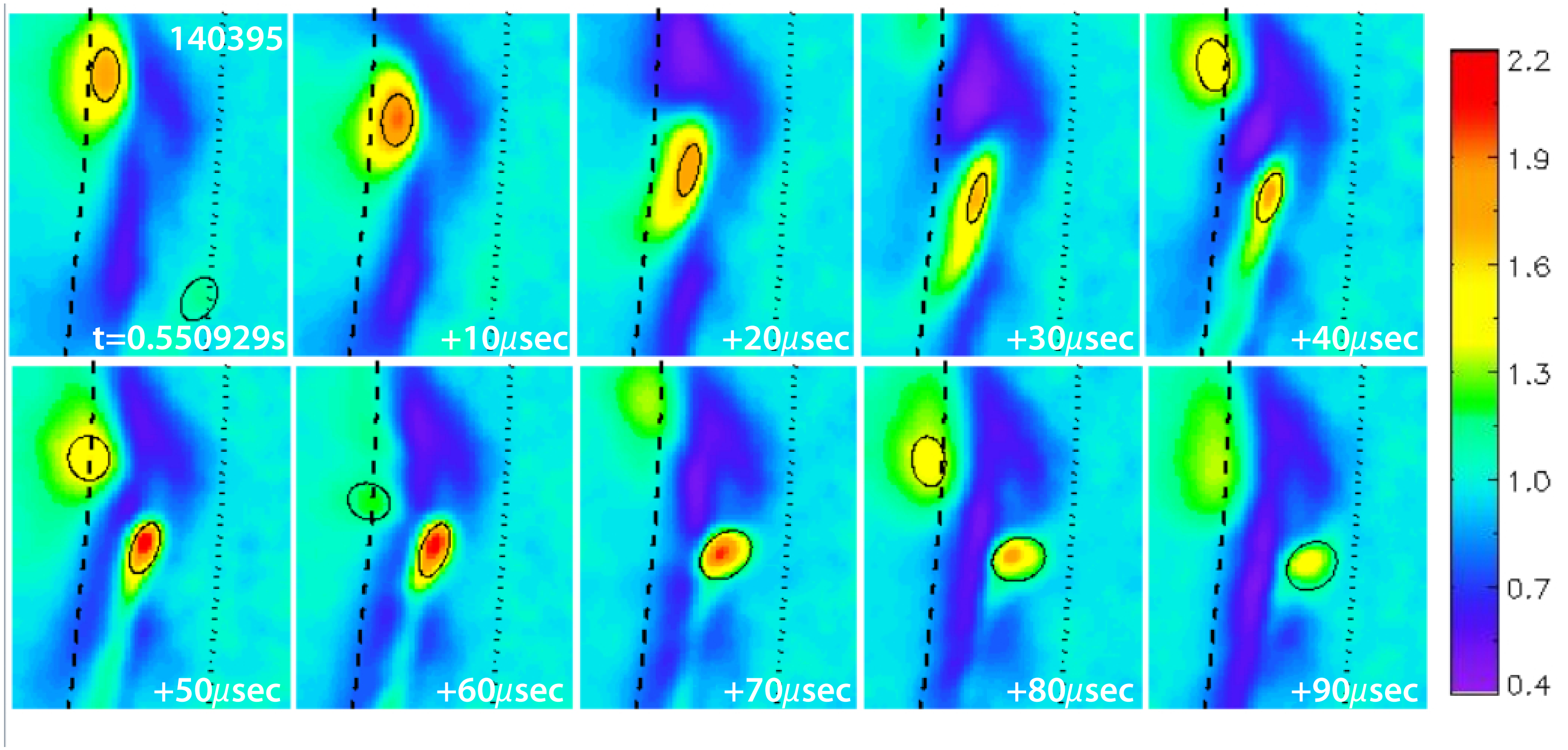
Time Dependence of GPI Signals

- 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. $I_p/B_t = 0.2 \pm 0.05$ 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

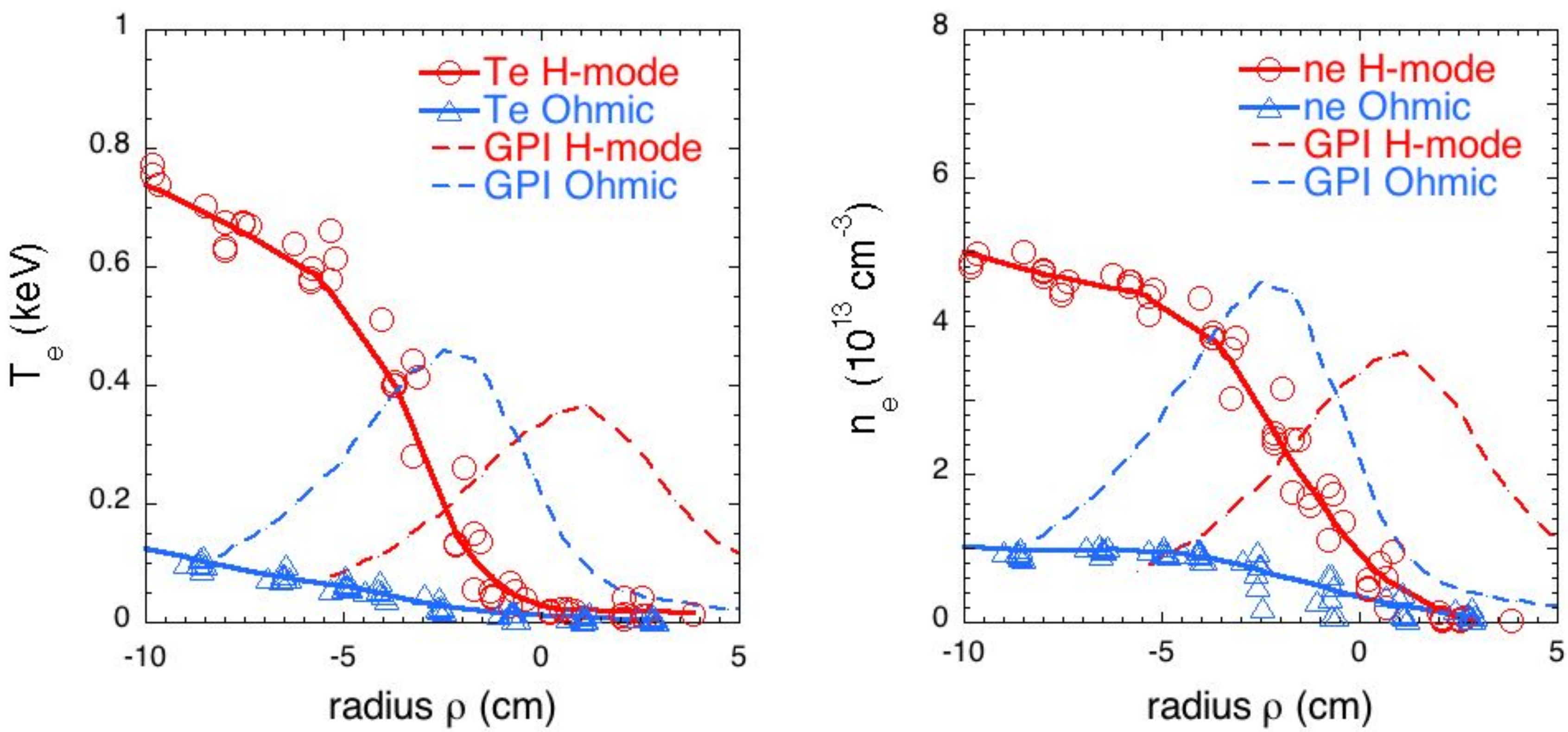
Sample plasmas used for profiles

	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

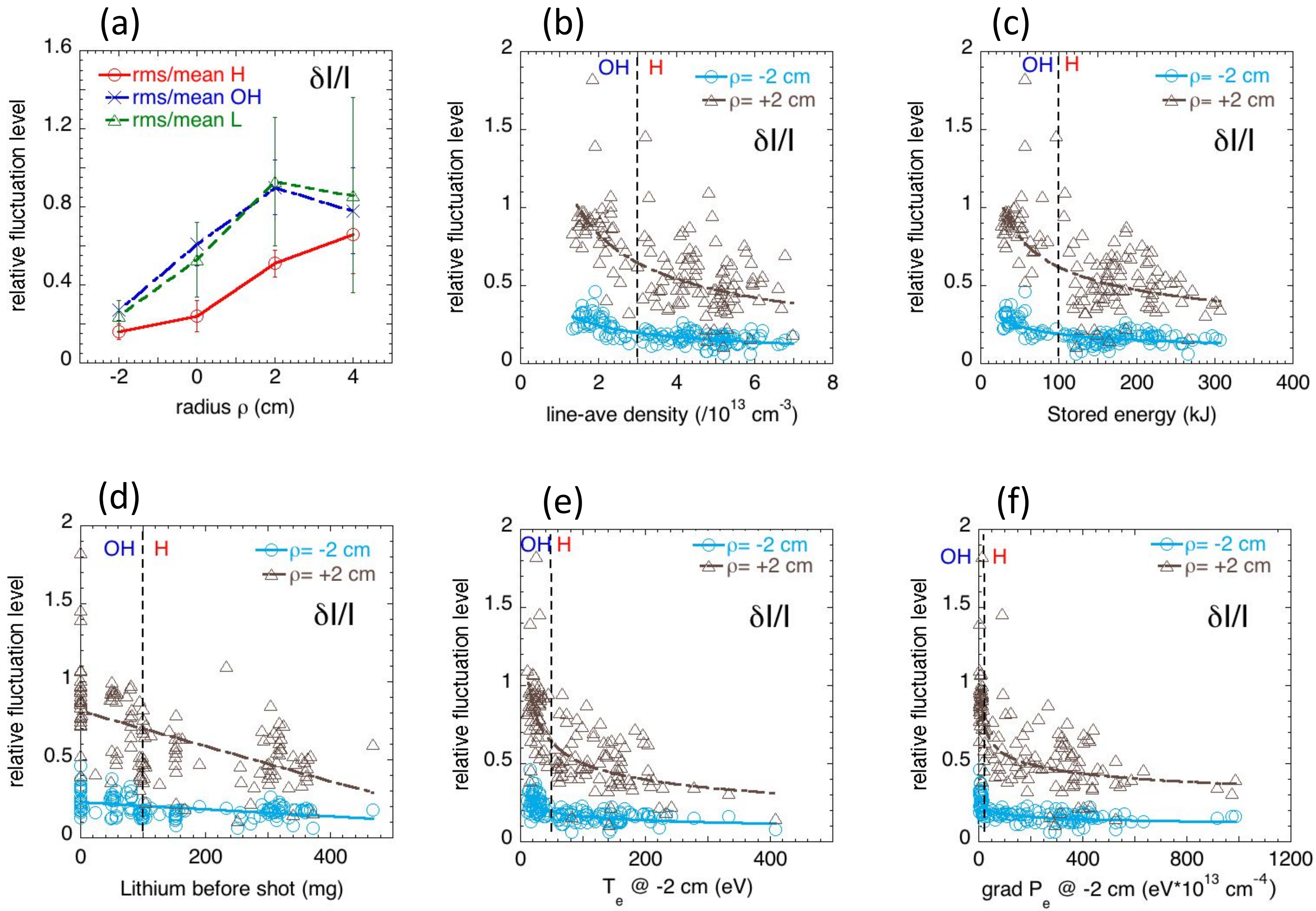
- Image data first normalized by average of images over ≥ 1 msec
- **Turbulence analysis** uses standard cross-correlation methods, averaging results over ±5 msec around peak of GPI signal
- **Blob analysis** tracks structures with height ≥ 1.5 x average height at that spatial position, averaging over ±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

Sample of Database Results and Analysis

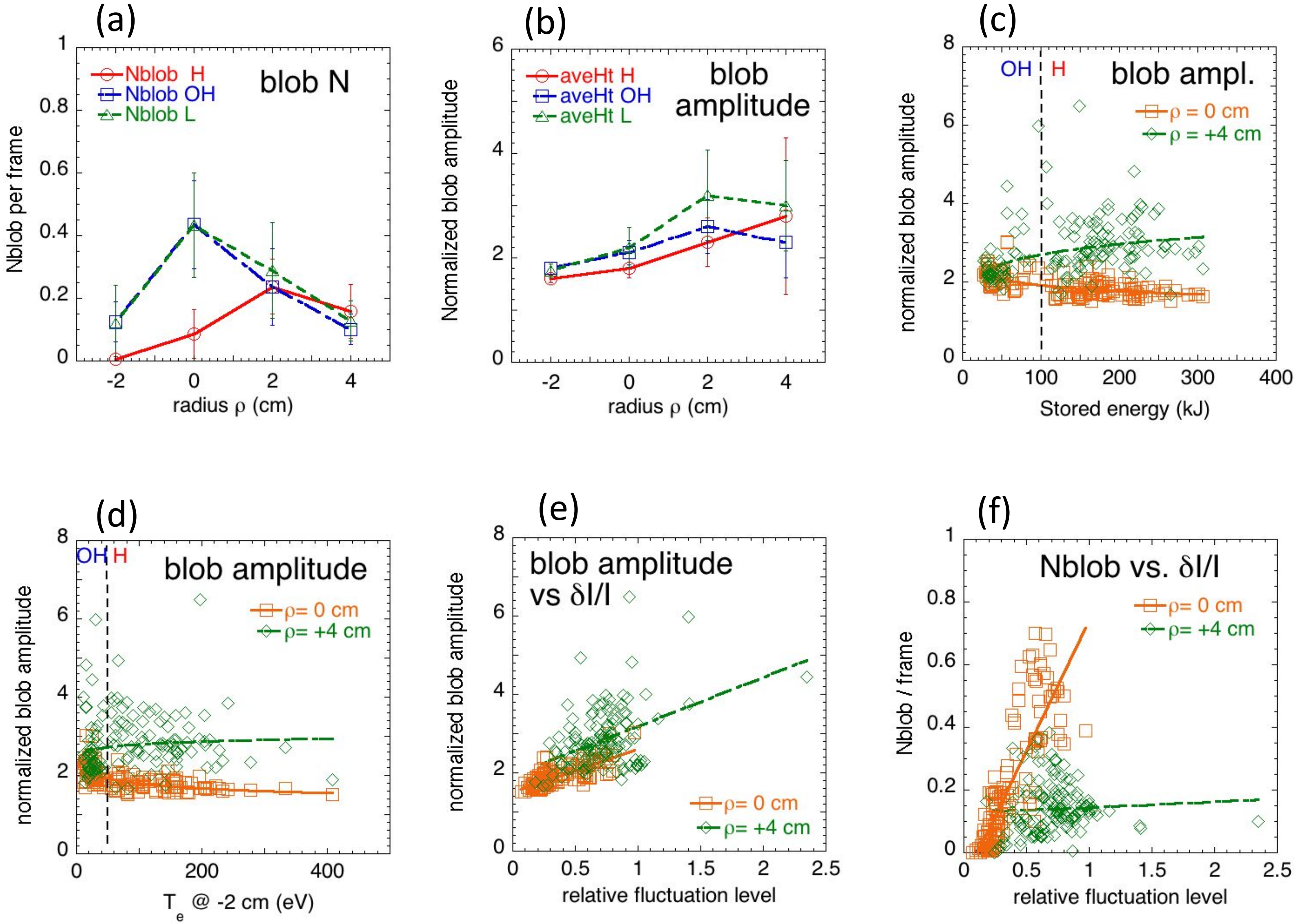
- Turbulence amplitudes - $\delta I/I$
- Blob amplitudes – N_{blob} and A_{blob}
- Turbulence size scales – L_{pol} and L_{rad}
- Blob size scales – blob L_{pol} and blob L_{rad}
- Poloidal turbulence and blob velocity – V_{pol} and blob V_{pol}
- Radial turbulence and blob velocity – V_{rad} and blob V_{rad}
- Cross-correlation and regression analysis – τ_{auto} and blob lifetime

whole database can be found at:
http://w3.pppl.gov/~szweben/NSTX2013/NSTX2013.html

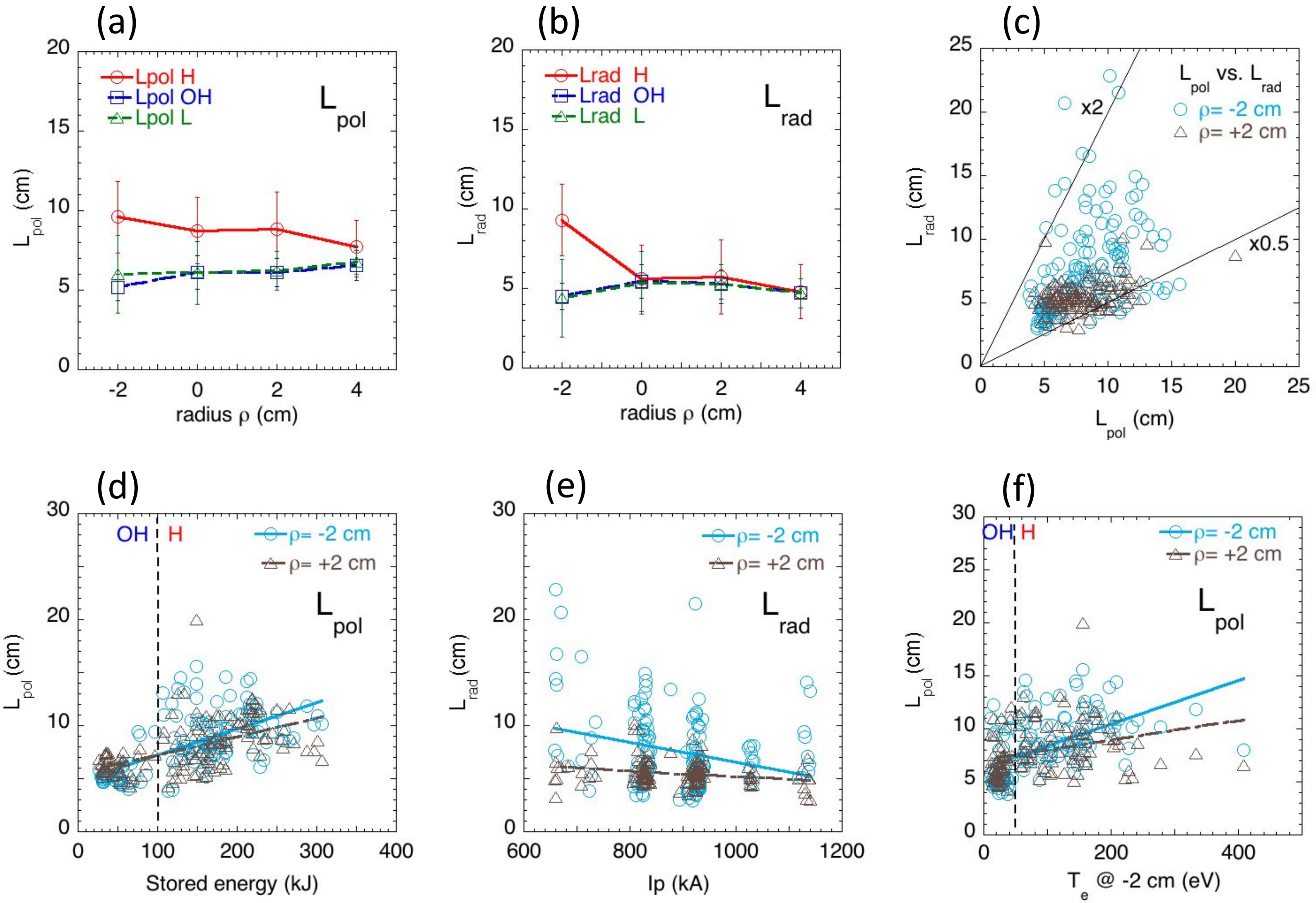
Turbulence Amplitudes



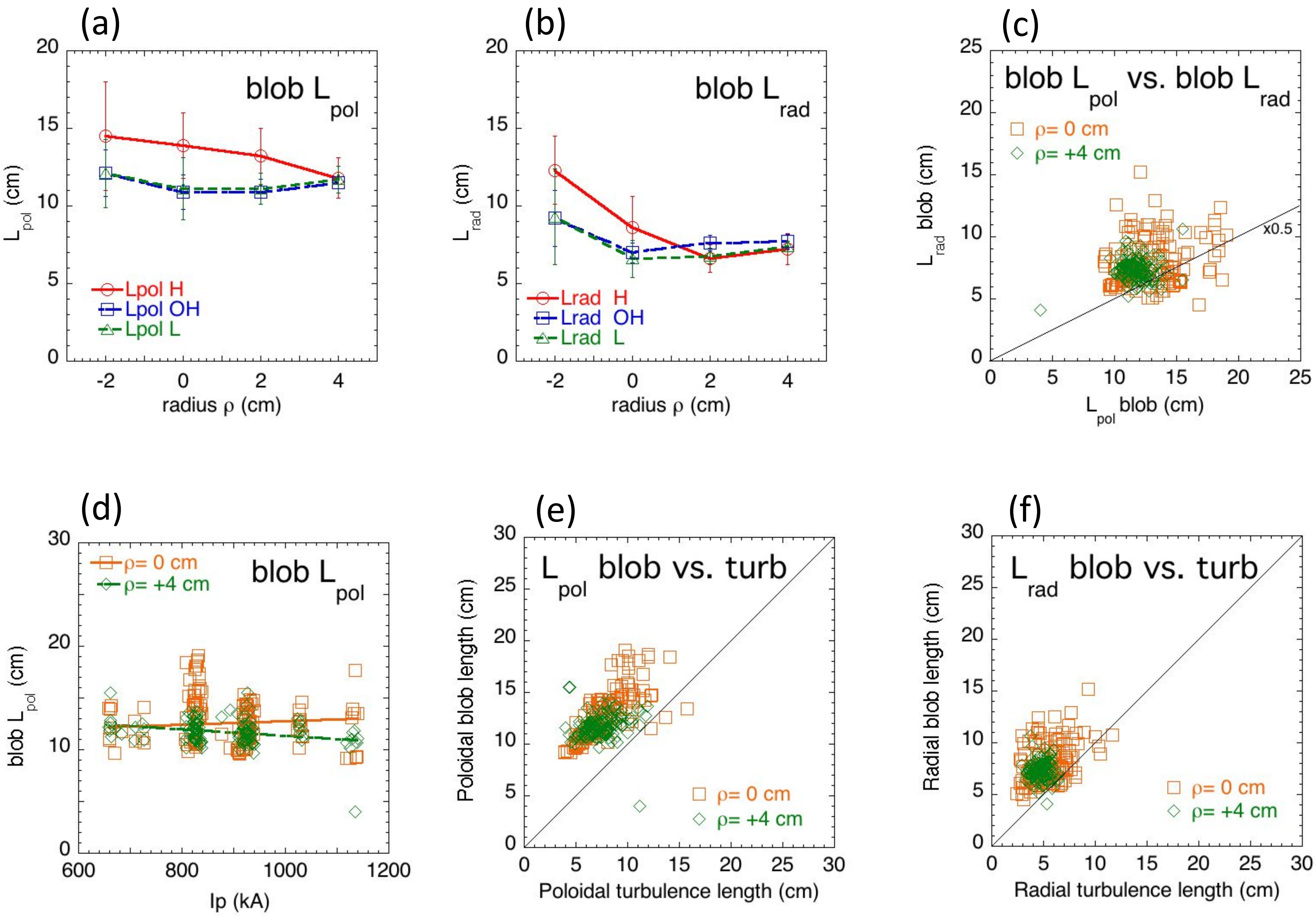
Blob Amplitudes



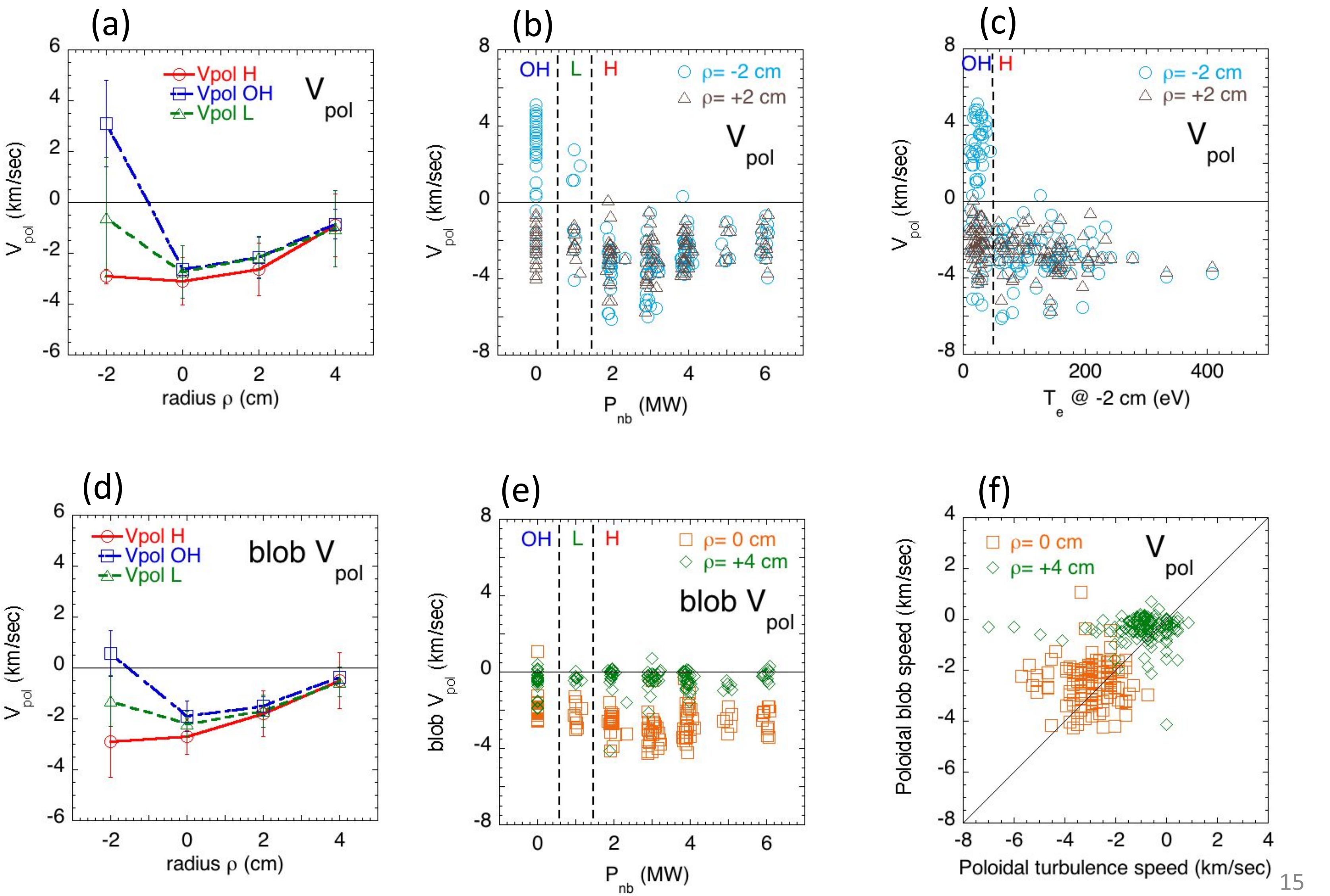
Turbulence Length Scales



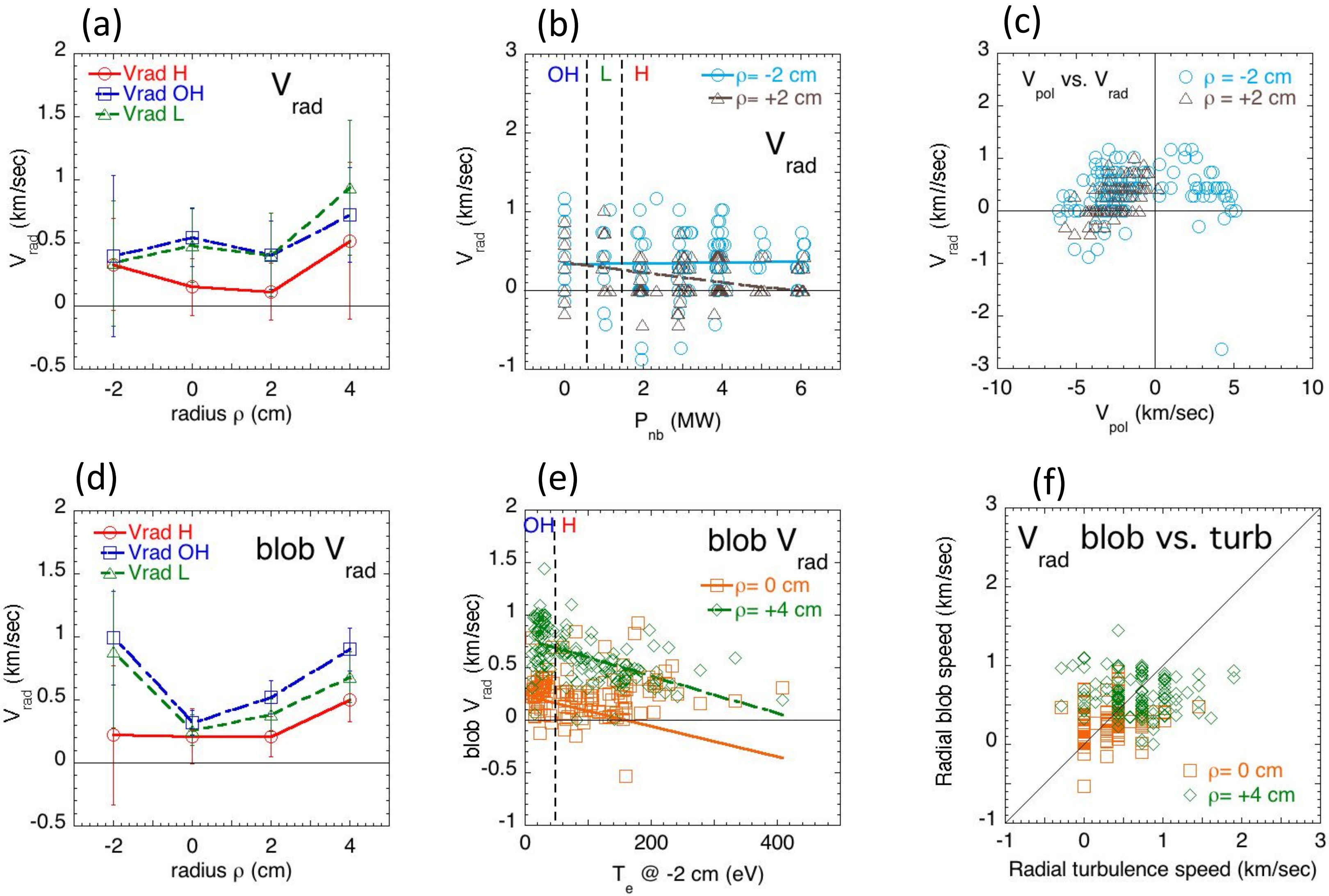
Blob Length Scales



Turbulence and Blob Poloidal Velocity

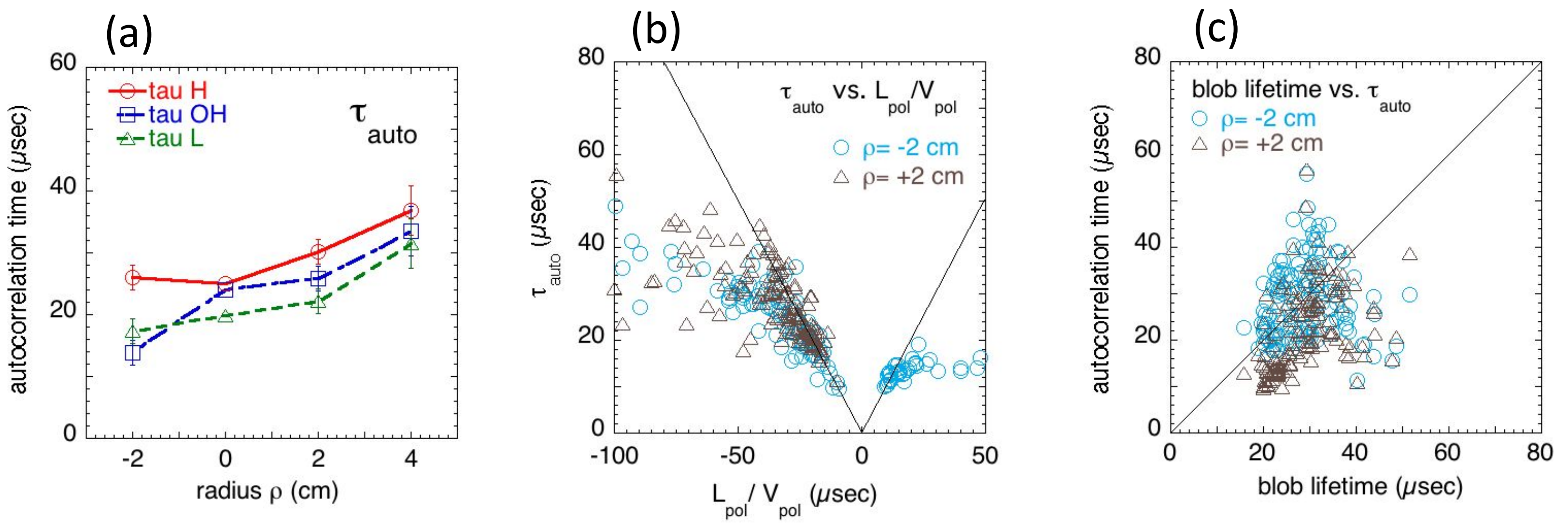


Turbulence and Blob Radial Velocity



Correlation Times and Blob Lifetimes

- Turbulence autocorrelation time increases with minor radius
- Autocorrelation time $\tau_{auto} \sim L_{pol}/V_{pol}$, approx. "frozen flow"
- Total blob lifetime in GPI viewing region ~ τ_{auto}



Turbulence Cross-Correlation Coefficients

showing only cases with ≥50% cross-correlation coefficient

	radius	B_t	P_{nb}	W_{mhd}	n_e-ave	Li/sh	edge n_e	κ
$\delta I/I$	-2 cm	0.53	0.57	0.63	0.69	-	0.62	-
	+2 cm	-	0.66	0.63	0.63	0.54	0.64	-
τ_{auto}	-2 cm	-	0.61	0.60	0.65	-	-	-
	+2 cm	-	-	-	-	-	-	-
L_{pol}	-2 cm	-	0.65	0.65	0.61	0.52	0.55	0.53
	+2 cm	-	-	0.54	-	0.51	-	0.55
L_{rad}	-2 cm	-	-	-	0.54	-	0.61	-
	+2 cm	-	-	-	-	-	-	-
V_{pol}	-2 cm	-	0.63	0.69	0.68	0.59	0.53	-
	+2 cm	-	-	-	-	-	-	-
V_{rad}	-2 cm	-	-	-	-	-	-	-
	+2 cm	-	-	-	-	-	-	-

Power Law Exponents for Turbulence

Single parameter (pair wise) exponents

	radius	B_t	W_{mhd}	n_e-ave	Li/shot	edge n_e	κ
δI/I	-2 cm	-1.7±0.29	-0.32±0.03	-0.52±0.05	-	-0.30±0.03	-
	+2 cm	-	-0.39±0.04	-0.61±0.07	-0.12±0.02	-0.37±0.03	-
τ_{auto}	-2 cm	-	0.39±0.03	0.62±0.05	-	-	-
	+2 cm	-	-	-	-	-	-
L_{pol}	-2 cm	-	0.37±0.03	0.55±0.05	0.09±0.01	0.29±0.04	2.92±0.04
	+2 cm	-	0.23±0.03	-	-	-	2.42±0.31
L_{rad}	-2 cm	-	-	0.64±0.07	-	0.36±0.04	-
	+2 cm	-	-	-	-	-	-

Multiple parameter (regression) exponents

	radius	I_p	B_t	ne-ave	Li/shot	W_{mhd}	κ	dn_e/dR
δI/I	-2 cm	-	*-0.88±0.31*		-	-	-	*-0.15±0.06*
	+2 cm	-	-	*-0.22±0.07*	-	-	-	-
τ_{auto}	-2 cm	-	-	*0.45±0.14*	-	-	-	-
	+2 cm	*0.97±0.24*	-	*0.41±0.13*	-	-	-	-
L_{pol}	-2 cm	*-0.62±.20*	-	-	-	-	*1.43±0.41*	-
	+2 cm	-	*-0.80±0.30*	-	-	-	*1.52±0.44*	-
L_{rad}	-2 cm	-	-	-	*0.08±0.02*	-	-	-
	+2 cm	-	-	-	*0.04±0.01*	*0.25±0.08*	*1.73±0.34*	*0.17±0.05*

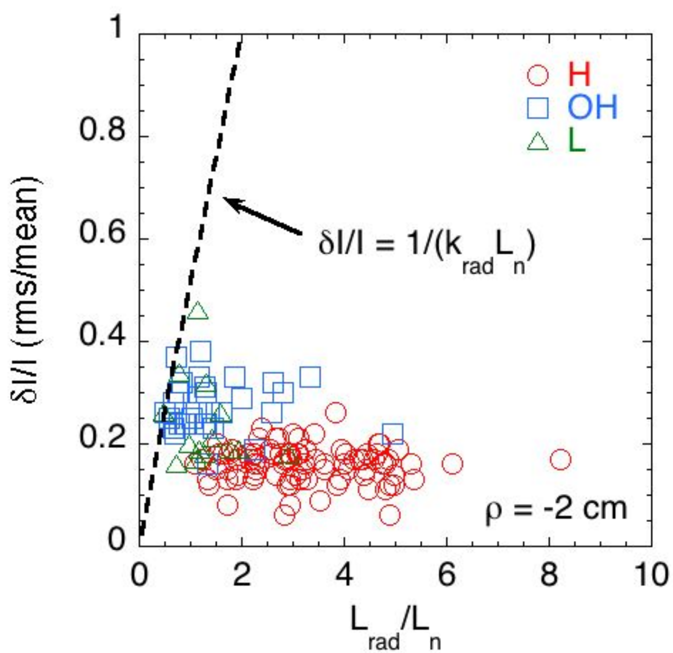
Summary of Some Turbulence Variations

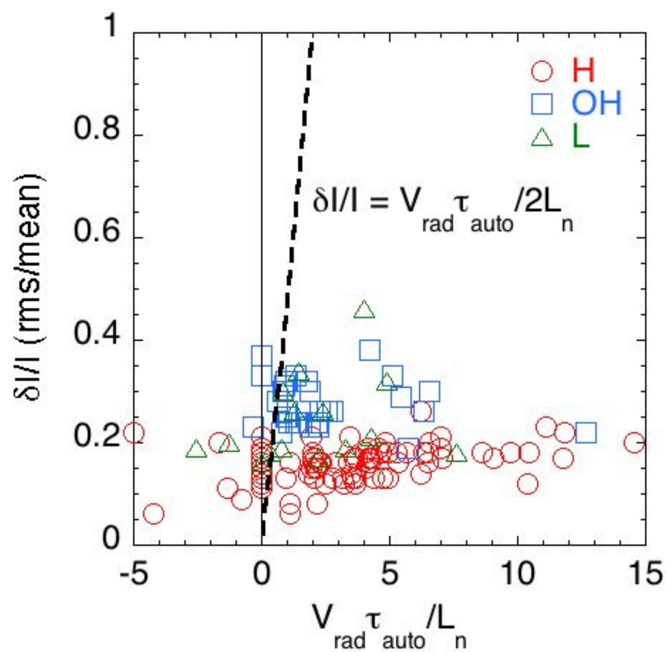
difficult to briefly summarize all the observed variations

- Relative fluctuation level increases with radius, but decreases with density, total stored energy, and edge T_e and grad P_e
- Poloidal and radial turbulence scale lengths are roughly constant vs. radius and within a factor-of-two of each other
- Poloidal velocity IDD except for EDD in Ohmic inside separatrix, and independent of density, stored energy, and P_{nb}
- Radial turbulence speed outward at 0-1 km/sec
- Blob properties generally similar to turbulence properties

Turbulence Amplitude vs. Theory

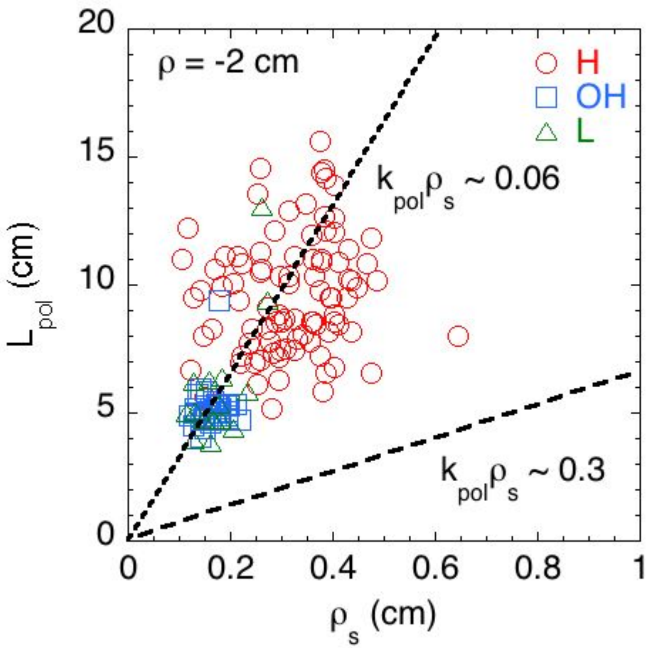
- Expect for saturation by wave breaking: $\delta n/n \sim 1/k_{rad}L_n$
- Expect for saturation of interchange modes: $\delta n/n \sim V_{rad}\omega/L_n$
- Assume $k_{rad} \sim 2/L_{rad}$, $\omega \sim 2/\tau_{auto}$, $\delta n/n \sim \delta I/I$ for GPI at ρ= -2 cm
- Measured $\delta I/I$ are below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

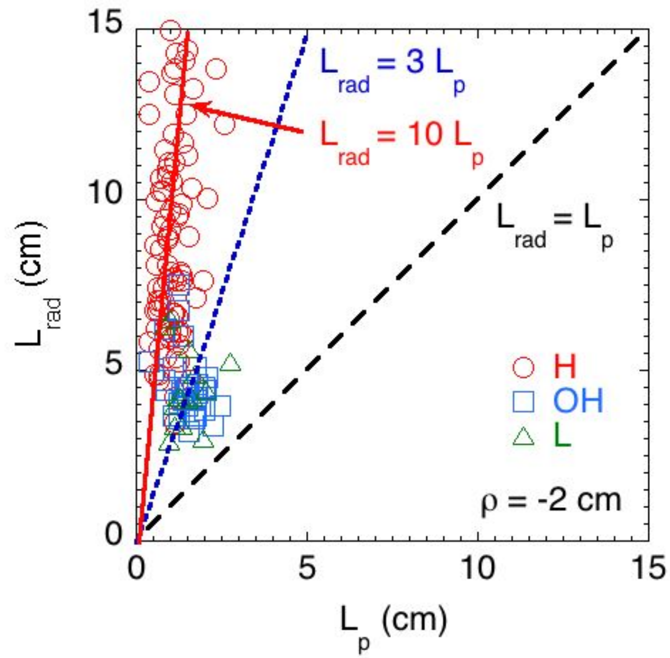




Turbulence Length Scales vs. Theory

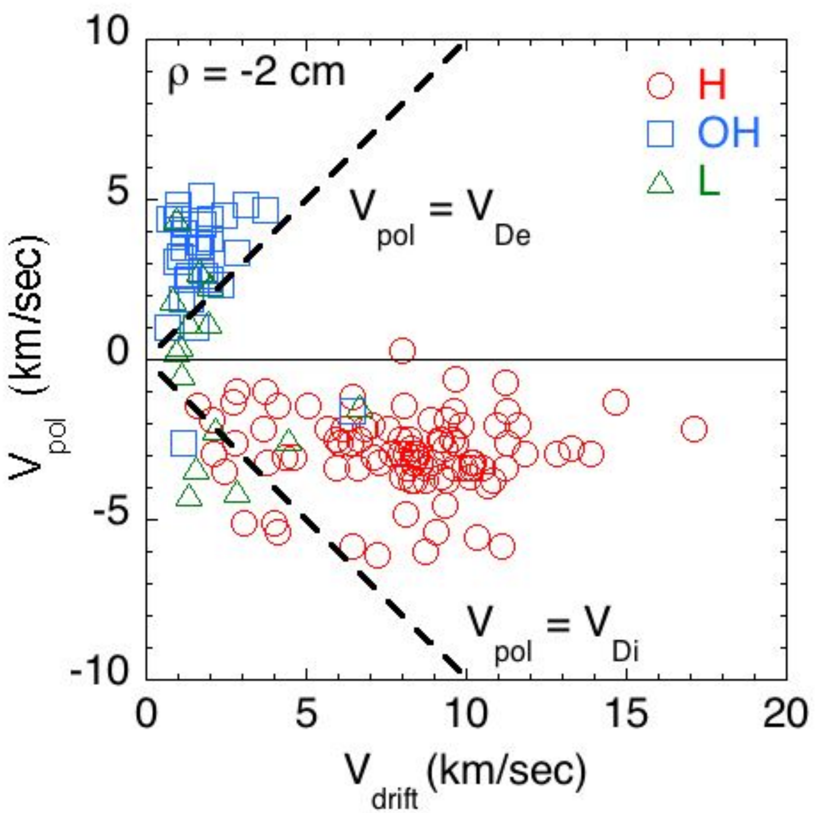
- Drift wave turbulence models have typically $k_{pol}\,\rho_s \sim 0.3$
- Interchange turbulence typically has $L_{rad} \sim L_{p(ressure)}$
- Measured size scales are ~3-5 times larger than these





Turbulence Poloidal Velocity vs. Theory

- 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:

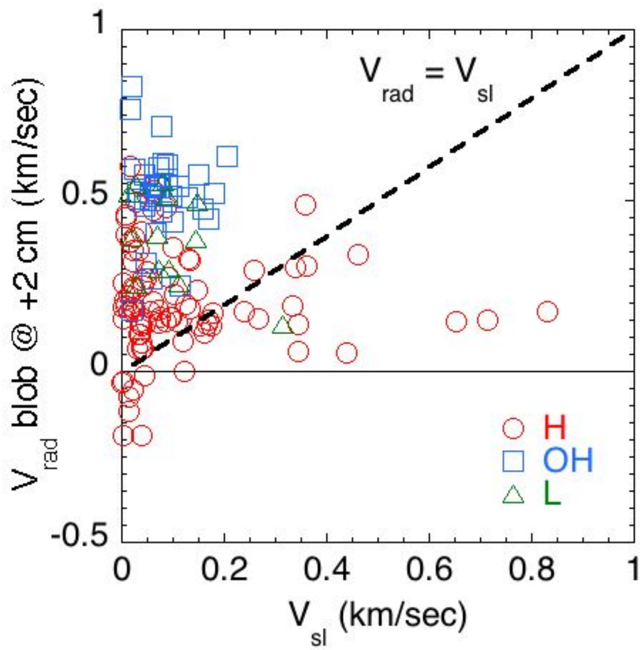
1) shift from e^- to i^+ drift waves

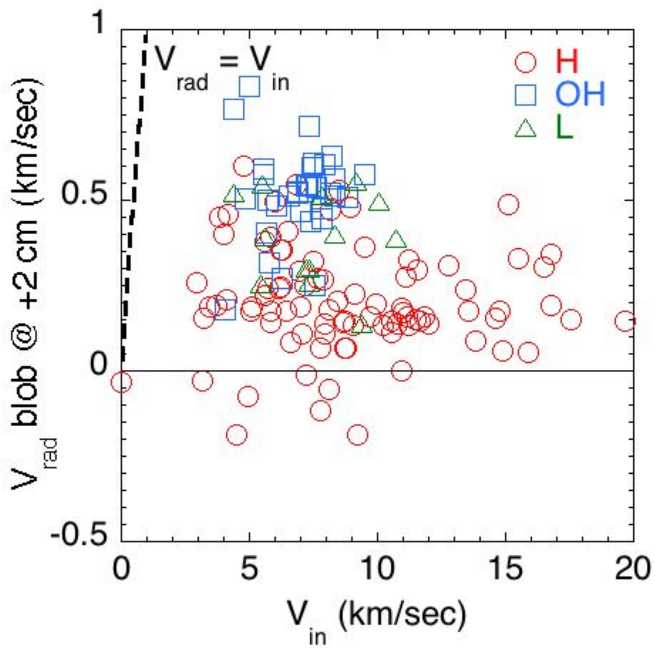
2) increased outward E_{rad}

3) NBI-induced toroidal rotation
   V_{pol} (NBI) ~ (B_p/B_t) V_{tor}
   V_{pol} (NBI) ~ - 1-10 km/sec (?)

Blob Radial Velocity vs. Theory

- 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 Comparisons with Theory

- Amplitudes of turbulence $\delta I/I$ at ρ = -2 cm in H-mode are lower than expected from simple theoretical estimates
- Poloidal turbulence size scale L_{pol} at ρ = -2 cm is in between simple drift-wave and interchange scale lengths
- Poloidal speed of turbulence V_{pol} 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

see Myra poster P13 for further theory analysis of database

Some New or Surprising Results

- No significant increase in the poloidal turbulence velocity with increased NBI power over P_{nb}~2-6 MW in H-mode plasmas
- The local radial correlation lengths just inside the separatrix in H-mode plasmas were ~2-5 times larger than the local density gradient scale, which seems inconsistent with drift wave theory
- There was relatively little variation of the turbulence or blob properties with respect to plasma current or toroidal field
- Although not new, there was a surprisingly clear reversal in poloidal turbulence velocity with radius in Ohmic plasmas
- Near absence of blobs inside the separatrix for H-mode plasmas

Overall Summary and Conclusions

- Edge and SOL fluctuation levels large in all shots in database, $\delta I/I \geq$ 15%-100%
- Turbulence correlation analysis and blob tracking analysis give similar results in almost all cases
- Could not find clear empirical scalings of turbulence variations with respect to global plasma or edge parameters
- Partial consistency with drift wave / interchange / blob models

Conclusion is that edge turbulence is not well understood