Edge Turbulence in Tokamaks

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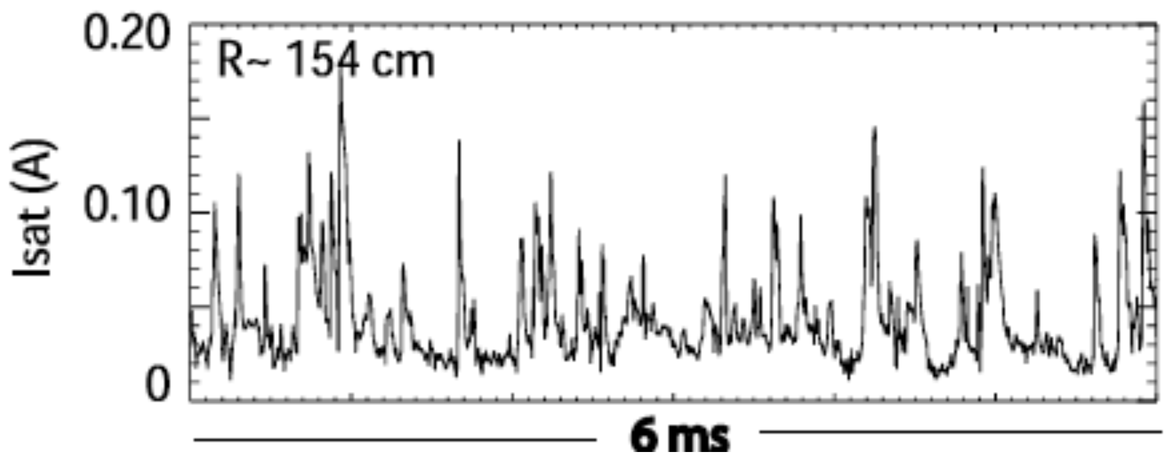
PPPL Theory
Jan. 9, 2015

- **Introduction and motivation**
- **Some NSTX/other experimental results**
- **Some relationships to theory/simulation**

thanks to:
R. Maqueda, D. Stotler, B. Davis, J. Terry (MIT), J. Myra (Lodestar),
and many other collaborators

What is Edge Turbulence ?



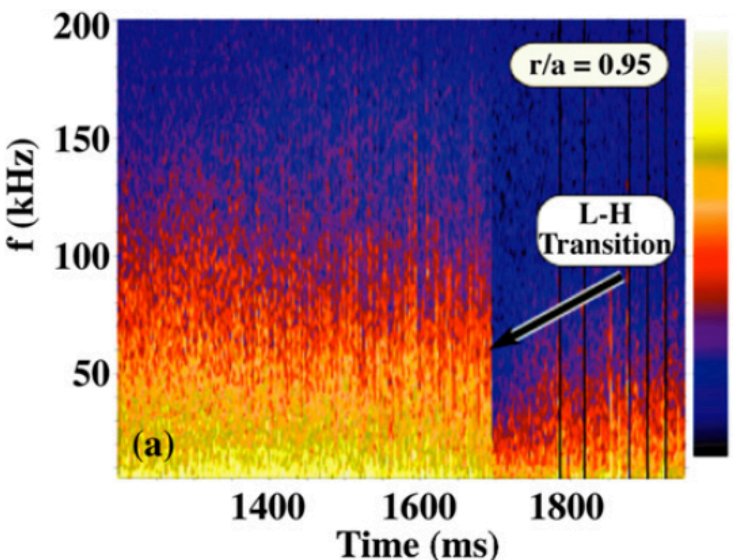
SOL density in NSTX

Boedo et al, PoP '14

- Large relative density fluctuations ñ/n ~0.1-1 @ r/a ~ 0.9 -> wall
- Broadband "turbulent" spectrum of ñ in frequency and size scale
- Edge is *almost always* strongly turbulent in tokamaks, stellarators, RFPs, simple tori (Torpex), and linear machines (LAPD)

Why is Edge Turbulence Important ?

- Turbulent transport influences heat and particle location at wall, e.g. to determine (in part) the "SOL width" at divertor plate
- Edge turbulence affects impurity influx, momentum transport, and external RF wave propagation through the edge
- Suppression of edge turbulence seems to cause the L-H transition



ñ from BES in DIII-D
McKee et al NF '09

What Physics is Necessary ?

- Density and temperature gradient driven drift waves and/or interchange modes seem to be important in edge/SOL

- Magnetic fluctuations or "MHD" effects seem to be small in edge/SOL transport (except H-mode pedestals & ELMs)

- Effects of open field lines, neutrals, and impurities on edge turbulence are not yet clear experimentally

not yet understood what is the minimum physics needed in theory/simulation to explain the observed edge turbulence

How is Edge Turbulence Measured ?

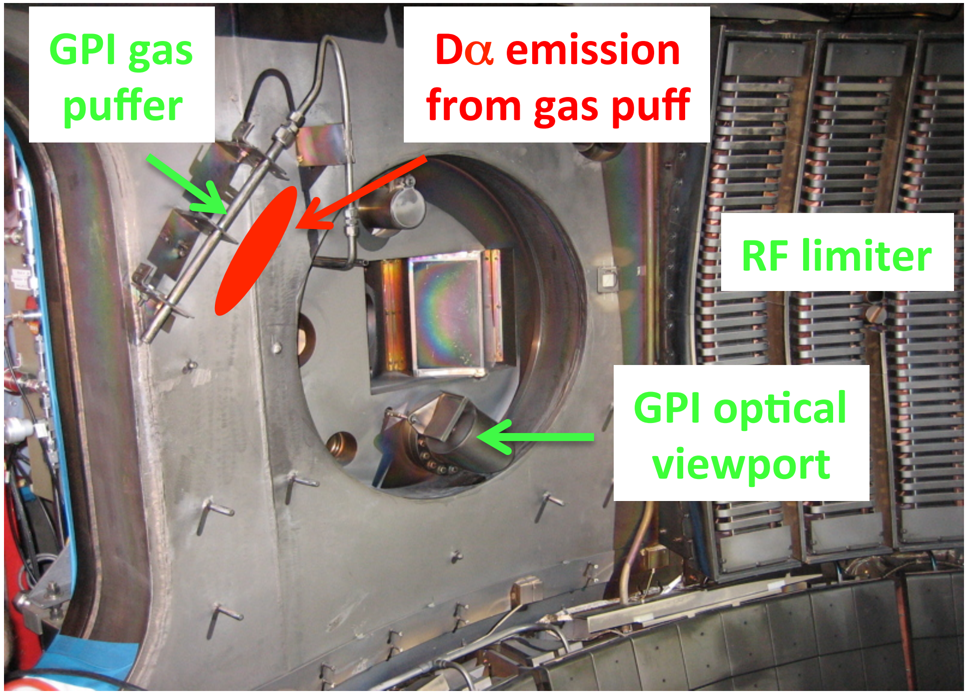
- Probes for region with $T_e \leq 100$ eV (fluctuations in n, φ, T_e, B)
- Electromagnetic wave scattering, reflectometry (μwave, FIR)
- Visible light emission from neutral atoms (BES, GPI, Li-BES)
- Heavy ion beam probe (fluctuations in n, φ)

Each diagnostic had its advantages and limitations

Cross-diagnostic comparisons have rarely been done

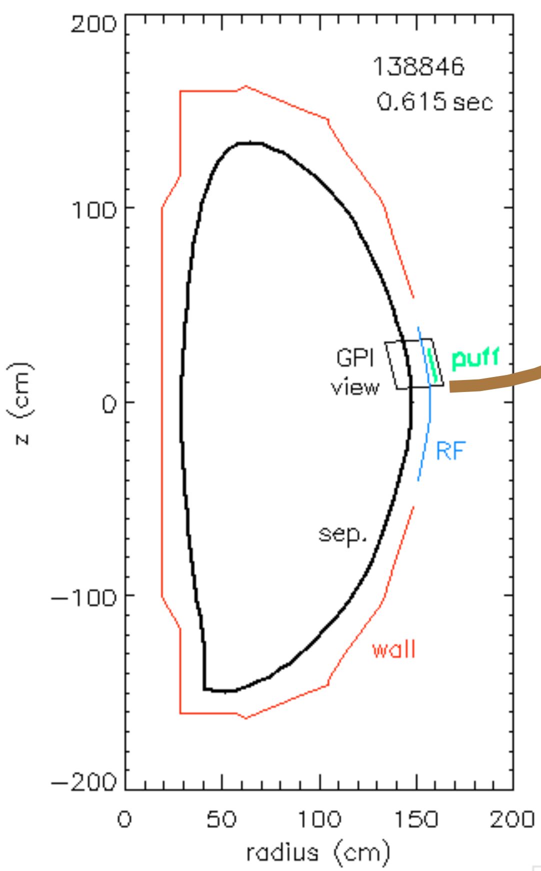
Gas Puff Imaging (GPI) Diagnostic on NSTX

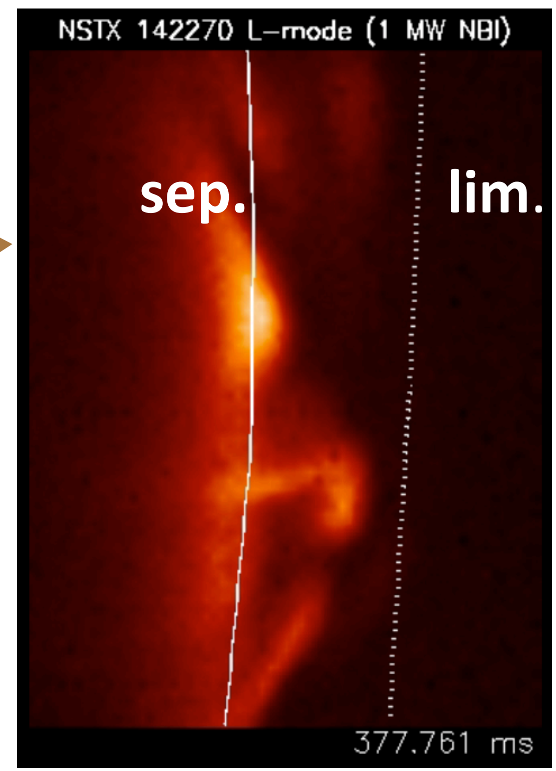
- D_2 gas puffed from pipe attached to outer wall above midplane
- Light emitted by D neutrals (Dα) viewed along B field direction
- Light emission responds as $I \sim n_o n_e^{\alpha} T_e^{\beta}$, where α~0.6-0.8 ($\beta<\alpha$)



NSTX Gas Puff Imaging (GPI) Movies

- GPI images visualize the spatial structure and motion of the edge turbulence within a ~5-10 cm wide radial "window" where the neutral D atoms radiate Dα light, roughly 5 eV < T_e < 200 eV





30 cm poloidal

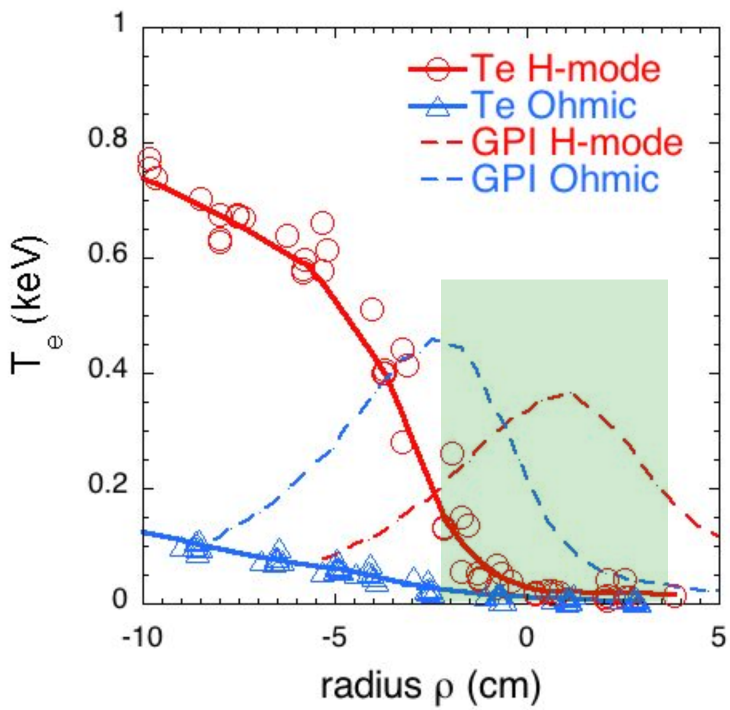
time in msec

5 minute GPI movie can be found at:

http://w3.pppl.gov/~szweben/Other_things/

Recent Analysis of NSTX GPI Data*

- Use database of 140 shots from 2010 run (OH, L, and H-mode)
- Focus on steady-state conditions (e.g. no ELMs, L-H transitions)
- Analyze turbulence in GPI images for radii ρ= -2 cm to +4 cm



edge parameters at ρ= -2 cm

	Ohmic	H-mode
T_e	23 eV	134 eV
n_e	0.37	0.92×10^{13} cm^{-3}
ρ_s	0.2 cm	0.3 cm
τ_{ei}	0.5 μsec	1.5 μsec
β_e	0.03%	0.5%

* S.J. Zweben et al, paper in preparation

GPI Turbulence Analysis

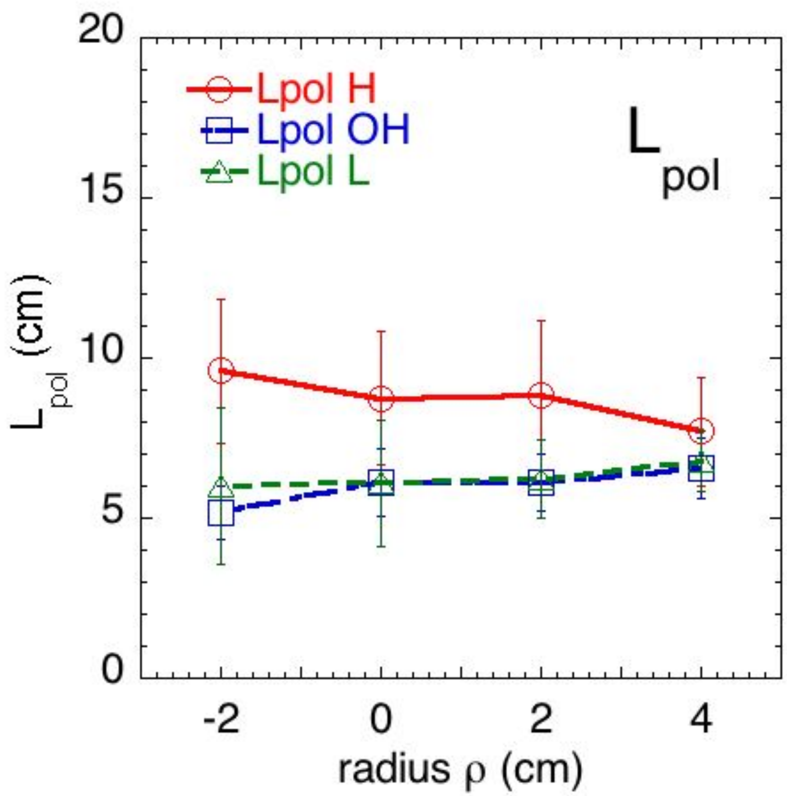
- Analyze 10 msec time period (4000 frames) for each shot
- Calculate 6 local turbulence quantities from cross-correlations:
  - Correlation lengths L_{pol}, L_{rad} (FWHM) - size scales of turbulence
  - Relative fluctuation levels $\delta I/I$ (rms/mean) - approximately $\tilde{n}/n$
  - Autocorrelation time (FWHM) - average timescale of turbulence
  - Turbulence velocity V_{pol}, V_{rad} - motion of turbulence patterns

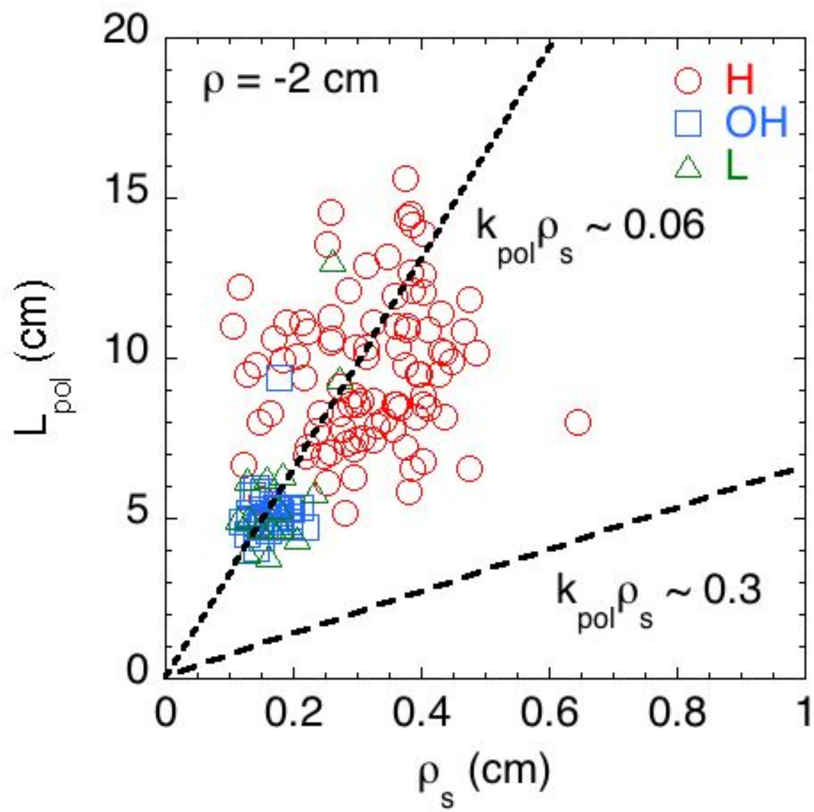
this analysis averages over entire (ω,k) spectrum of turbulence

results are generally typical of all tokamaks (and stellarators)

Turbulence Scale Lengths

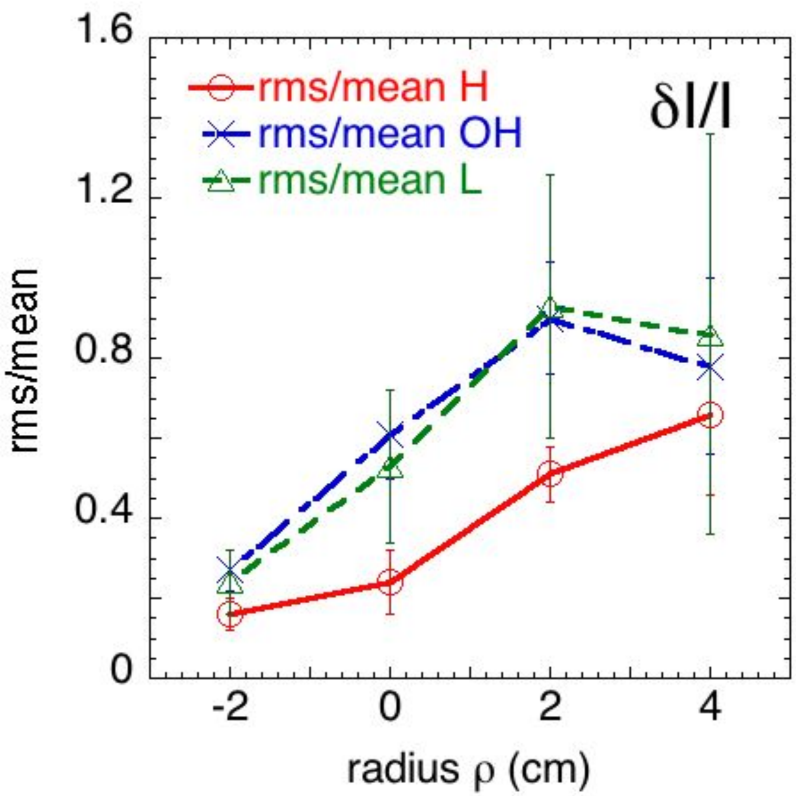
- Poloidal correlation length $L_{pol} >> \rho_s$; $L_{rad} \sim (0.6\text{-}0.8)\ L_{pol}$
- Fits $k_{pol}\rho_s \sim 0.06$ at $\rho = -2$ cm, assuming B_o and $L_{pol} \sim 2/k_{pol}$
- Seems roughly consistent with drift-wave like scaling

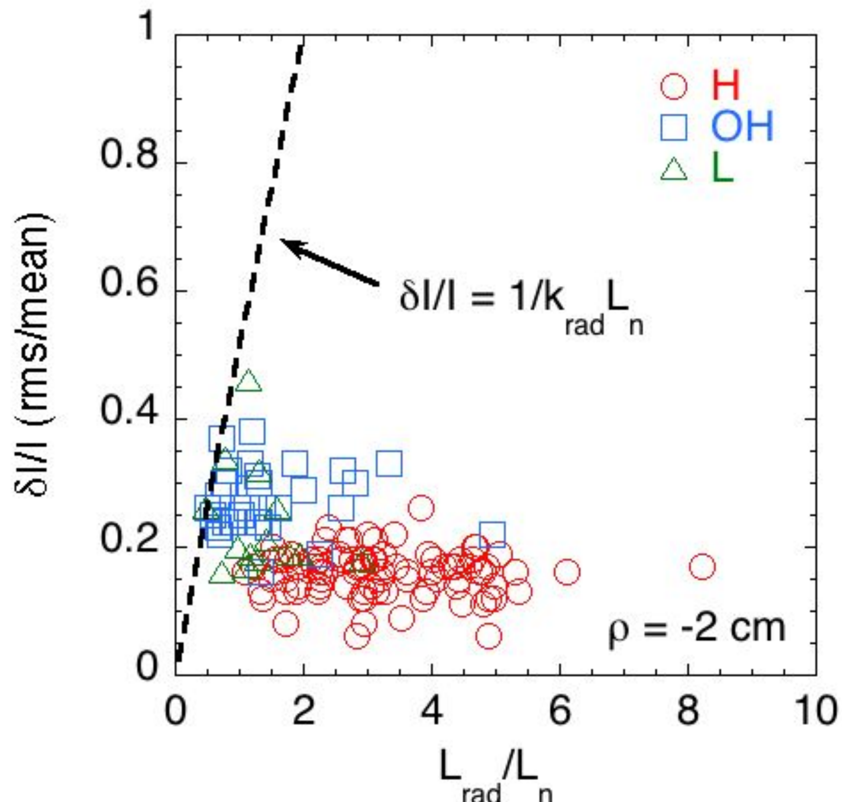




Relative Fluctuation Levels

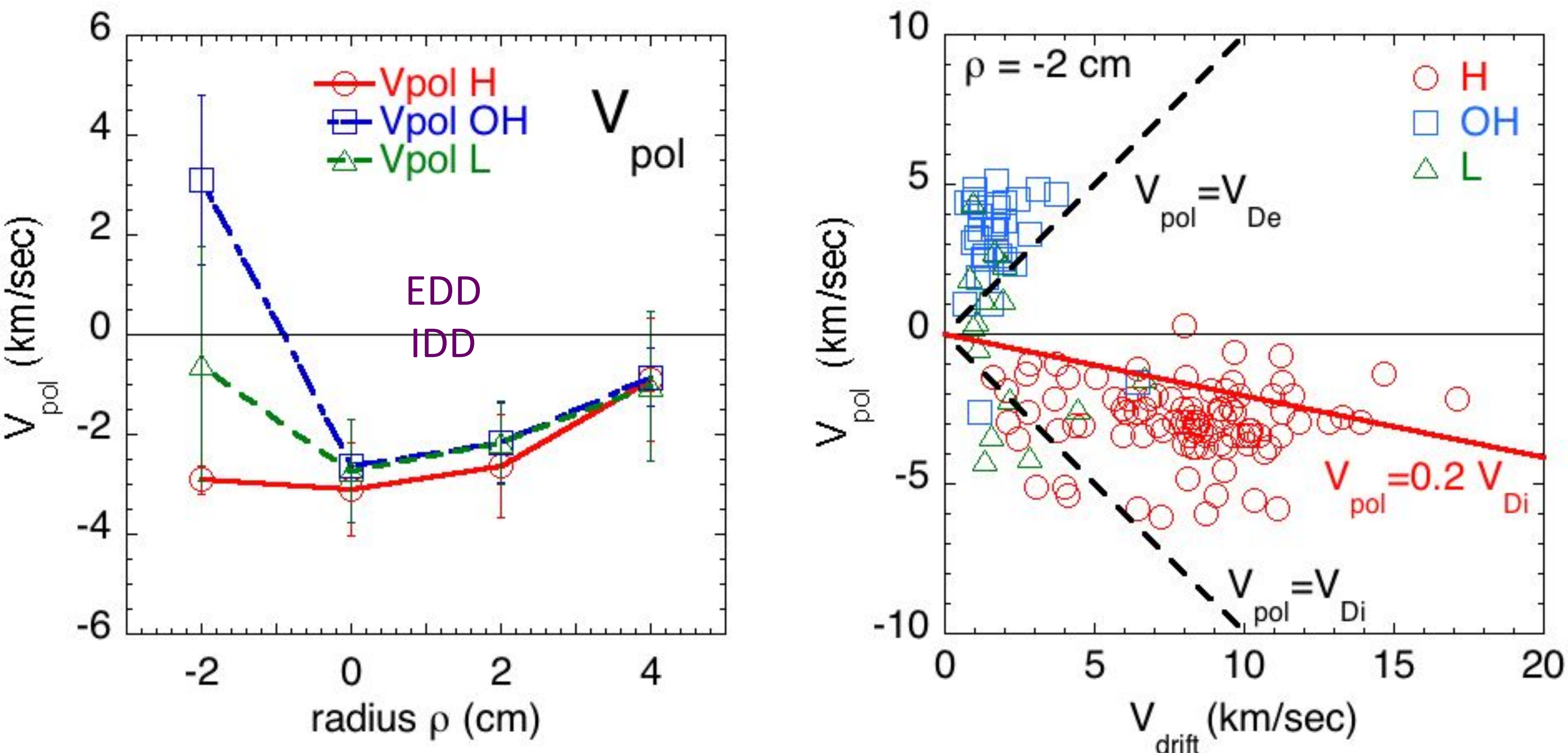
- Relative fluctuation level δI/I ~ ñ/n increases across separatrix
- Lowest fluctuation levels in H-mode still δI/I ~ 0.07 (ñ/n ~ 0.10)
- δI/I ~ $1/k_{rad}L_n$ (wave-breaking limit) at ρ = -2 cm, except H-modes





Poloidal Turbulence Velocity

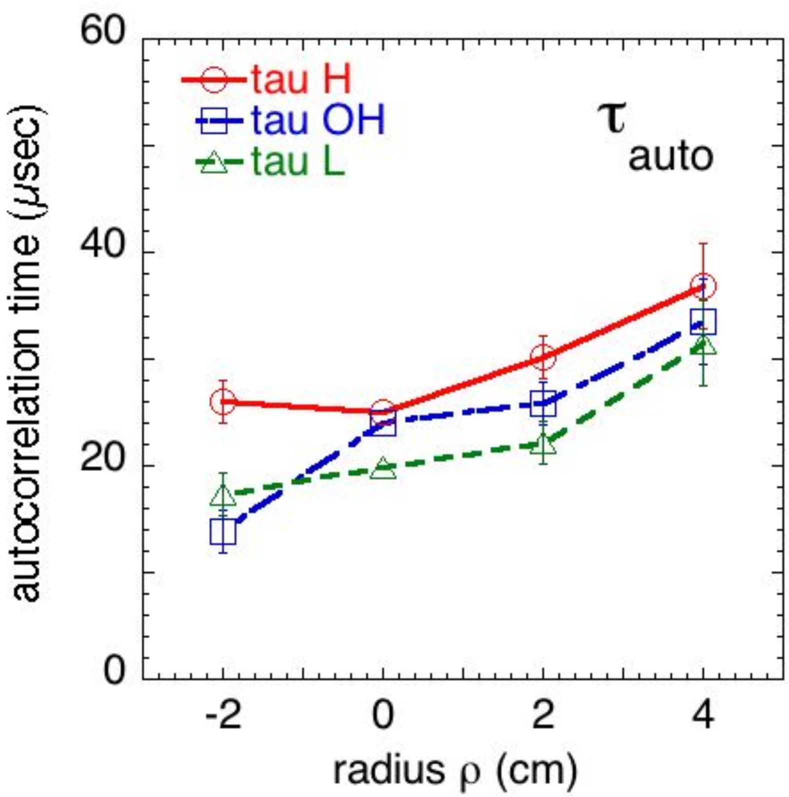
- $V_{pol} \leq 3$ km/sec, measured by time-delayed cross-correlation
- $V_{pol} \sim (1\text{-}2)V_{De}$ for Ohmic, $V_{pol} \sim (0.2\text{-}0.4)\ V_{Di}$ for H-modes
- Effects of edge plasma rotation, NBI not yet determined

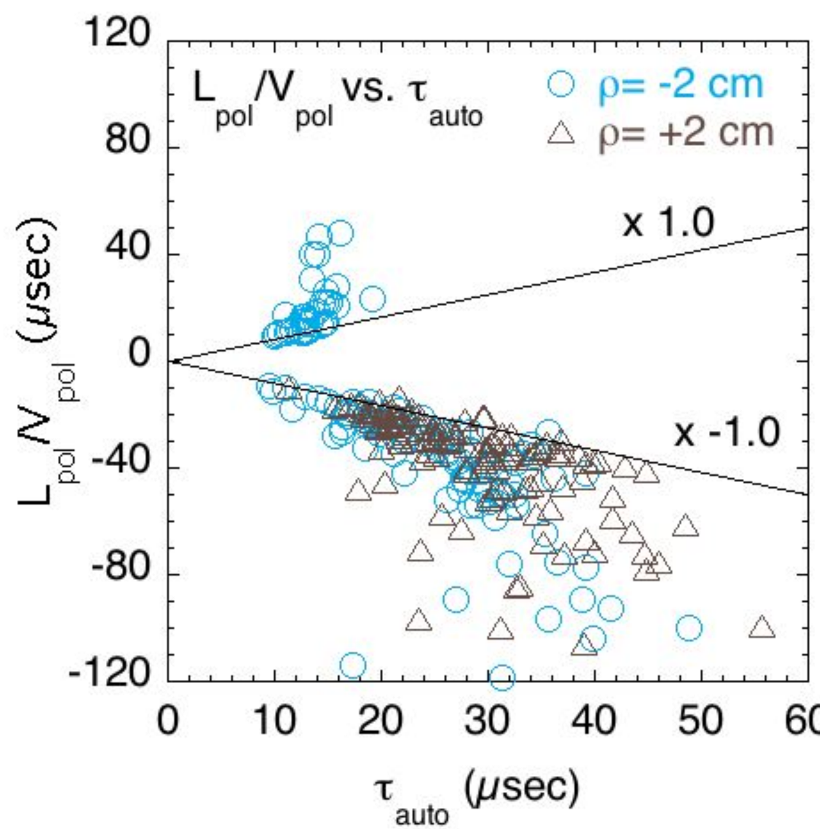


Turbulence Timescales

- Autocorrelation times slightly increasing across separatrix
- $\tau_{auto} \sim L_{pol}/V_{pol}$ implies ~ "frozen flow" in poloidal direction,

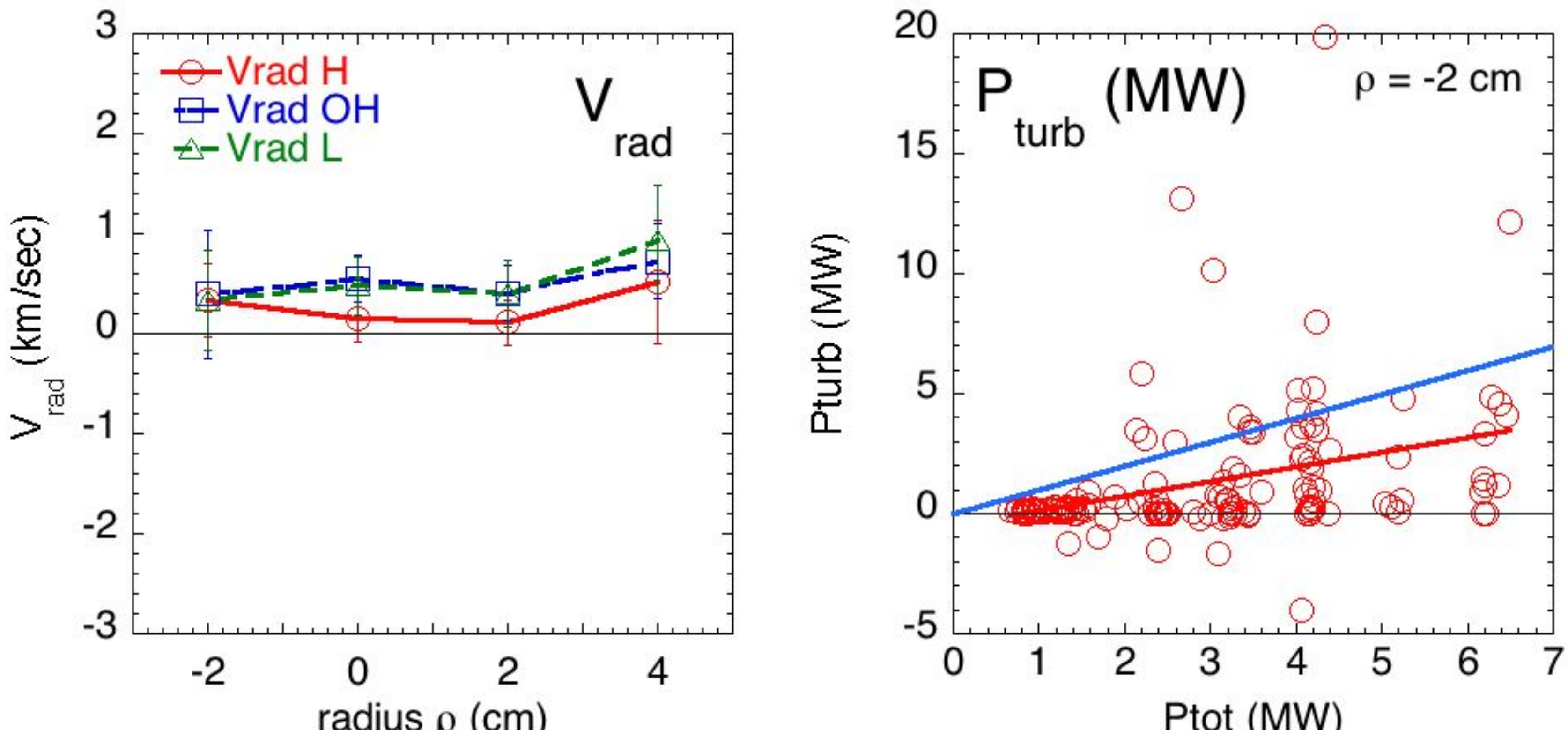
  but only true when $V_{pol} >> V_{rad}$ (not always the case)





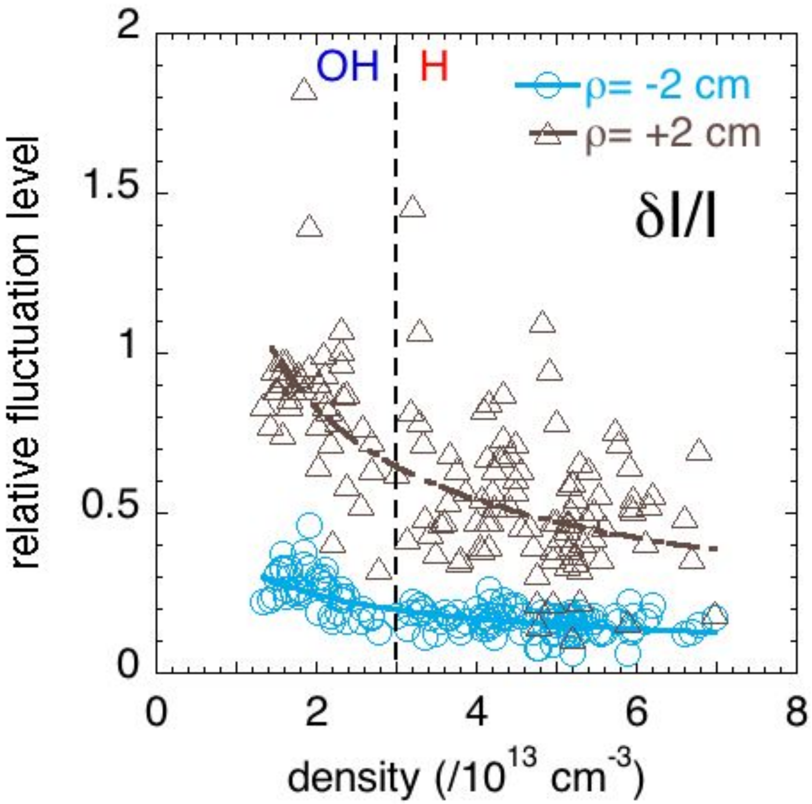
Radial Turbulence Velocity

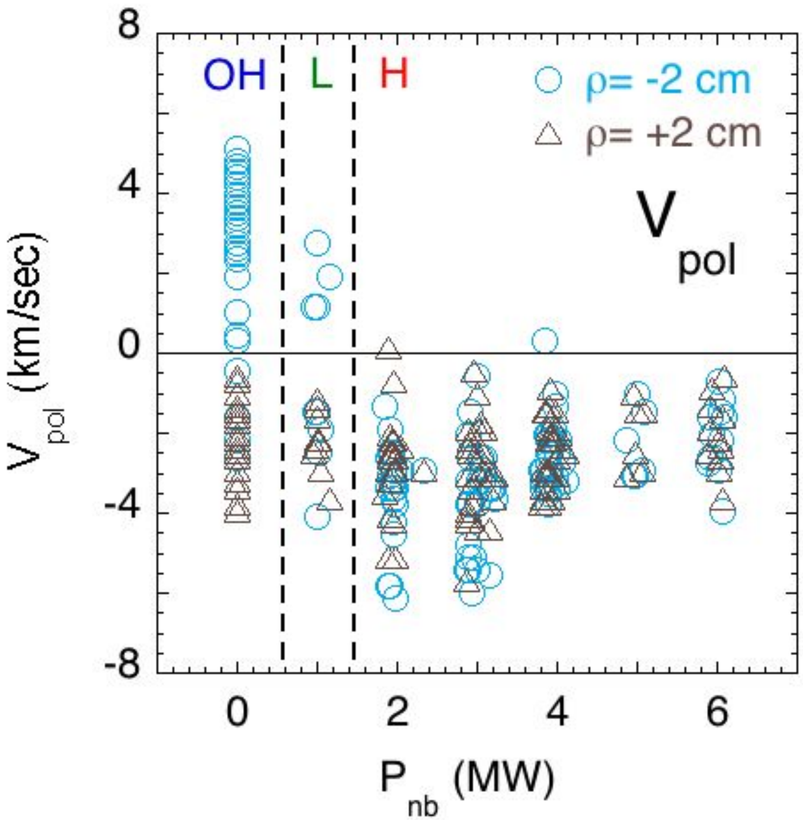
- V_{rad} ~ 0.2-1 km/sec outward (1 km/sec is speed of a rifle bullet)
- Can estimate radial power loss as $P_{turb} = 5/2 \langle \delta p \delta V_{rad} \rangle$, assuming $\langle \delta p \delta V_{rad} \rangle \sim (\delta I/I) n_e T_e V_{rad}$, and loss at ±45º around midplane
- Resulting P_{turb} ~ 0.6 P_{tot} on average, but with a lot of scatter



Variations with Global Parameters

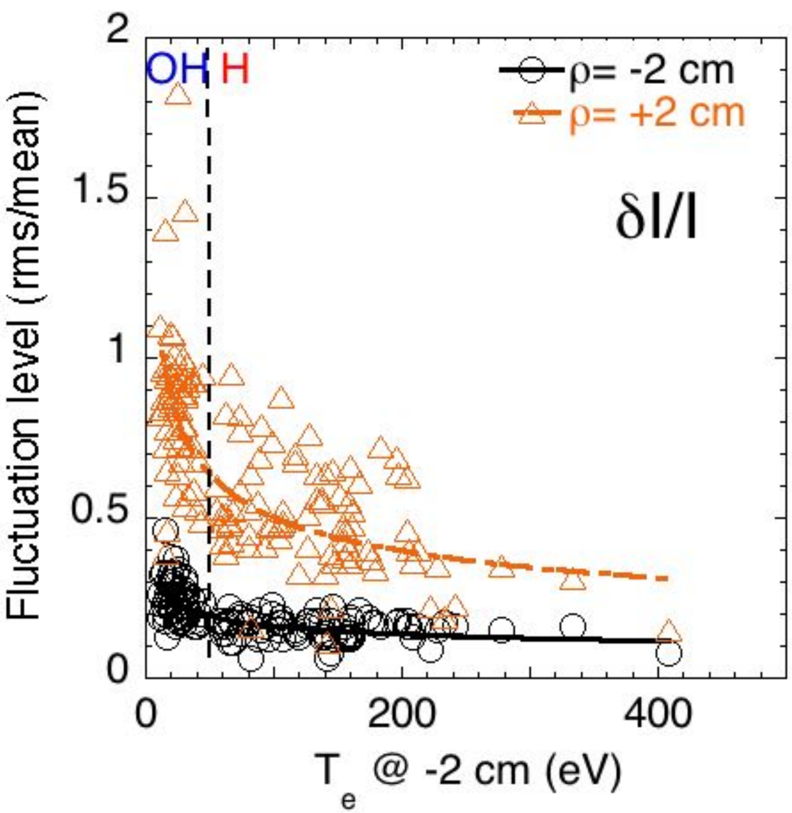
- $\delta I/I$ decreases with $<n_e>$, mainly with OH -> H-mode variation
- V_{pol} does not increase with NBI power in H-mode (surprisingly)
- Difficult to separate co-depencences of $<n_e>$, P_{nb}, W, Lithium

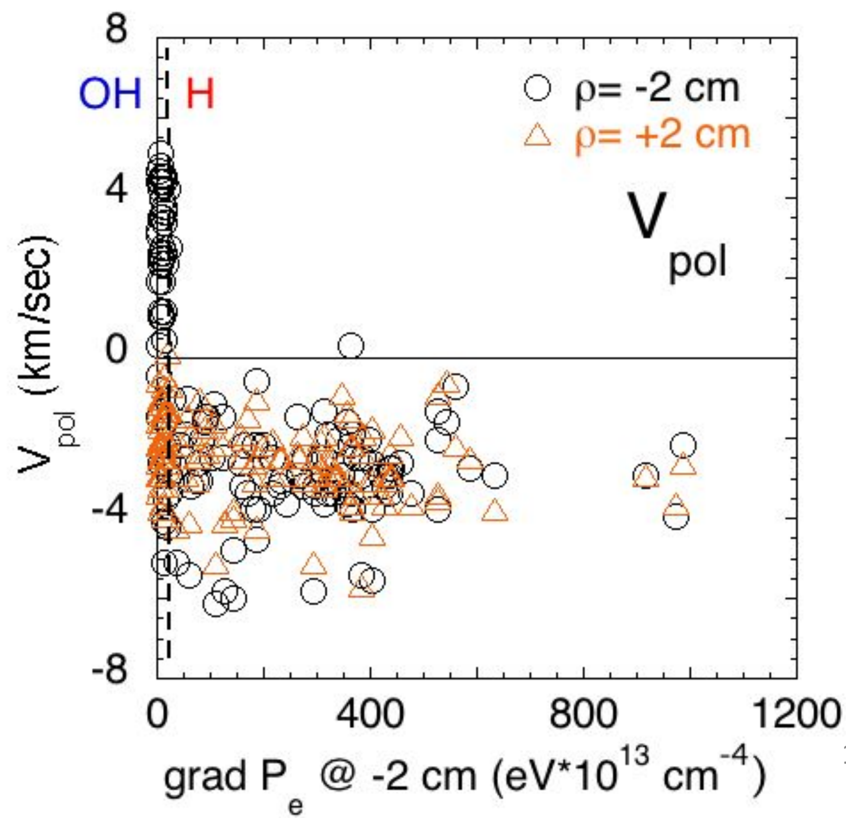




Variations with Edge Parameters

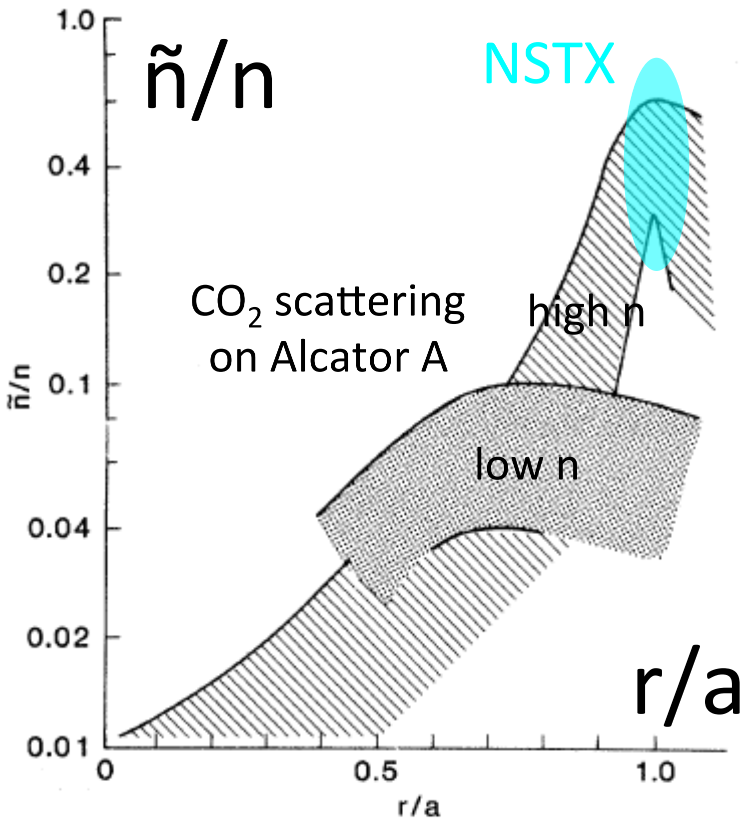
- $\delta I/I$ decreases with edge T_e, partially OH -> H-mode variation
- V_{pol} does not increase with edge grad P_e in H-mode (surprisingly)
- Probably these trends tied to “H-mode physics”, e.g. shear flow

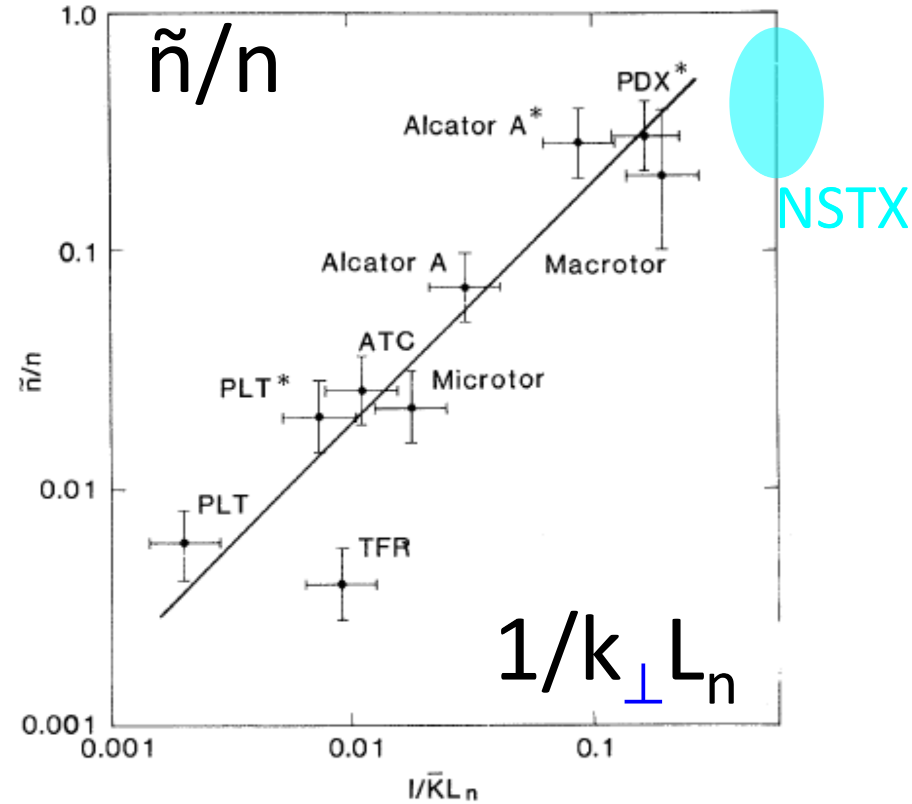




Some Comparisons with Other Devices

- Large level of edge density fluctuations has been seen on many tokamaks, along with rough $\tilde{n}/n \sim 1/k_\perp L_n$ scaling

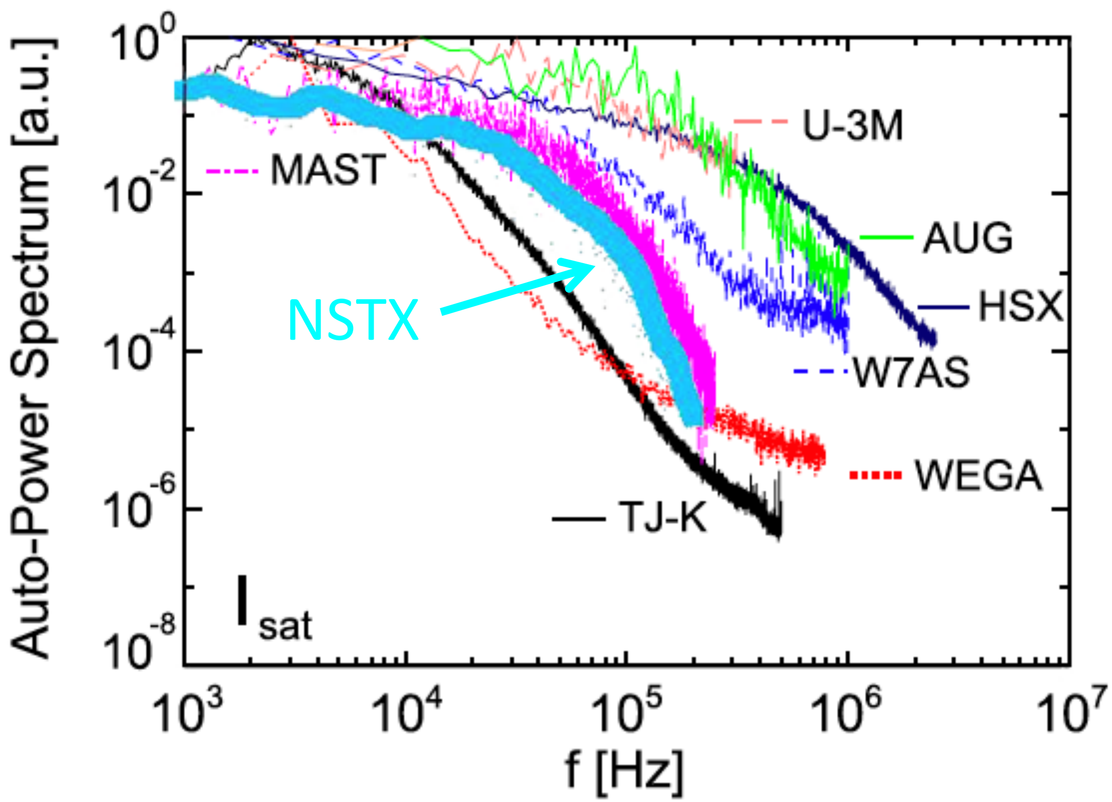




C. Surko and R. Slusher, "Waves and turbulence in tokamak fusion plasmas", Science (1983)

Comparison of Frequency Spectra

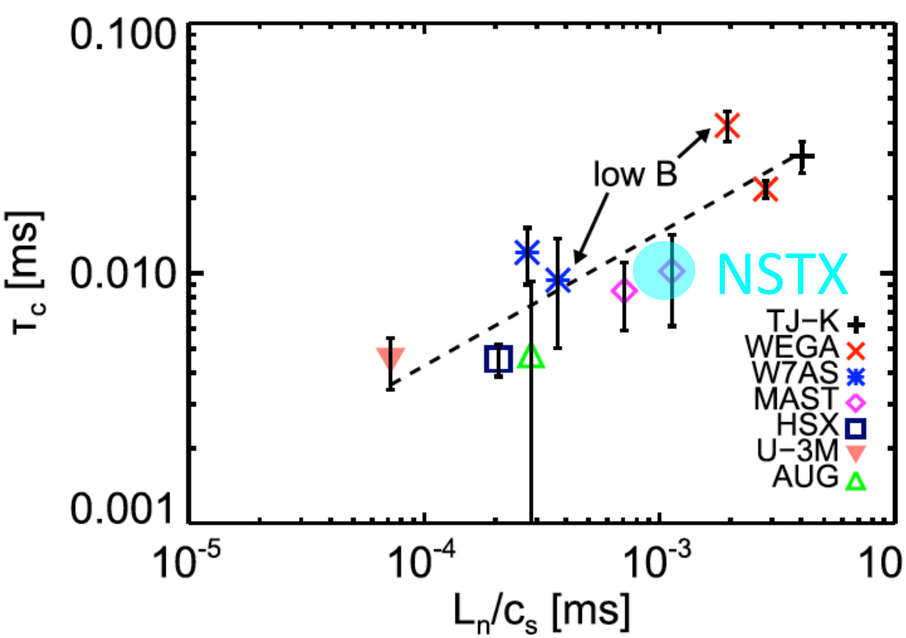
- Broad frequency spectrum of I_{sat} in probes near separatrix for 5 stellarators and 2 tokamaks (NSTX ~ MAST)

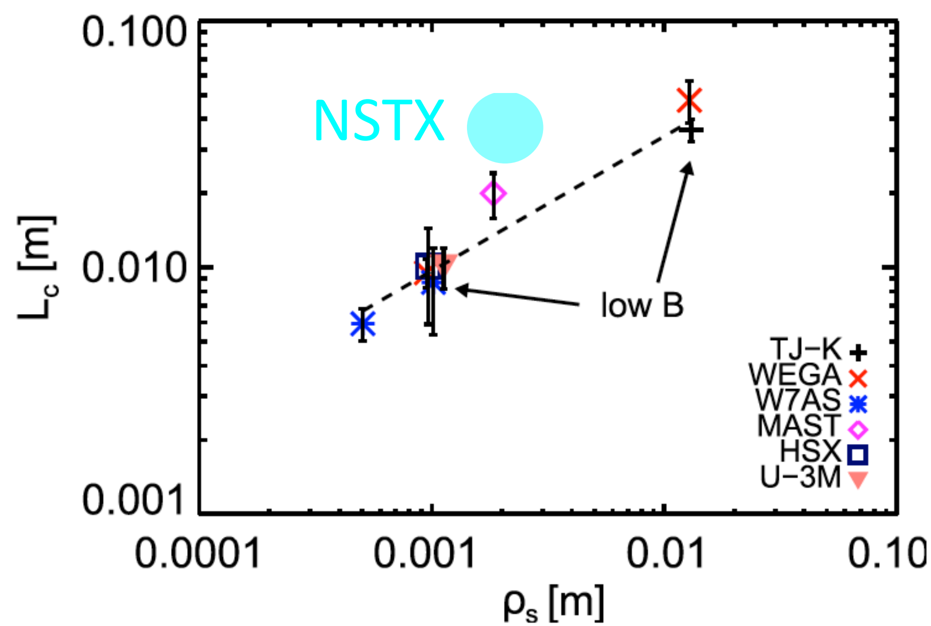


P. Simon et al, "Scaling and transport analysis based on an international edge turbulence database", PPCF 2014

Scaling of Correlation Time and Length

- NSTX result in L-mode similar to MAST, as expected
- Cross-machine data fit by: $\tau_c \sim (L_n/c_s)^{0.5-0.6}$ & $L_c \sim (\rho_s)^{0.5-0.6}$





P. Simon et al, "Scaling and transport analysis based on an international edge turbulence database", PPCF 2014

Relationships to Theory/Simulation

- Earliest theories of edge turbulence relied on simulations of nonlinear equations (e.g. Hasegewa et al, PRL 1983)

- Many modern simulation codes for tokamak edge turbulence
  - NLET (Maryland/IPP)
  - BOUT & BOUT++ (LLNL/York)
  - ESEL (Riso)
  - SOLT (Lodestar)
  - GEMR, GEMX (Scott)
  - GBS (Lausanne)
  - XGC-1 (Chang, Ku)
  - also relevant work by Sarazin (Cadarache), Bisai (IPR India), Angus (UCSD), Garcia (Tromso), Naulin (Riso) and others

Lodestar Edge Turbulence Code (SOLT)

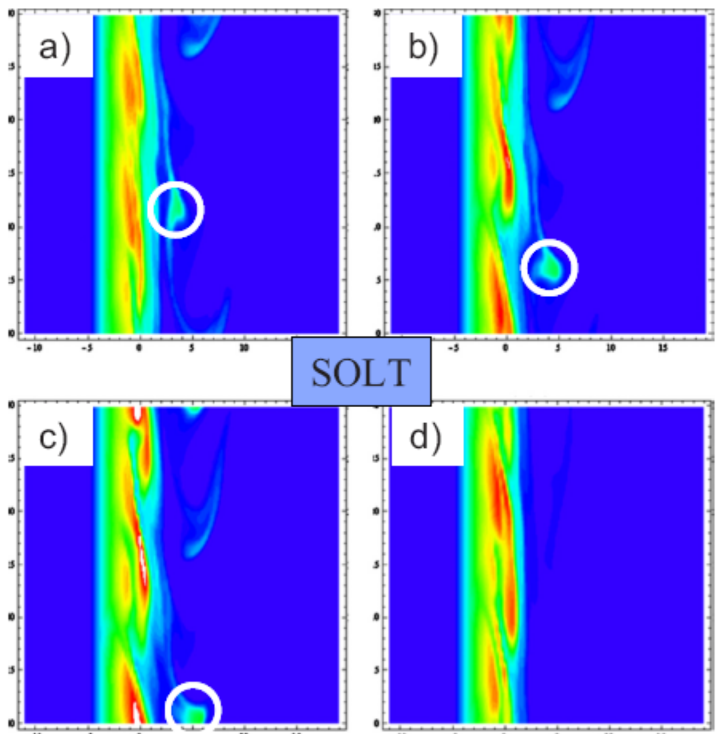
- 2-D ($\perp$B) electrostatic fluid model, using reduced-Braginskii eqs.
- Includes both open and closed field line regions near separatrix
- Equations for generalized vorticity (incl. $j_{||}$), density, T_e and T_i
- Includes models for sheath physics and parallel heat flux in SOL
- No separation of profiles and order-unity fluctuations
- Inputs n, T_e, T_i profiles (inside separatrix) and parallel connection length $L_{||}$ to divertor plate from experiment
- Inputs ad-hoc high-k dissipation and flow damping

$\Rightarrow$ **Outputs edge turbulence, including drift waves and "blobs"**

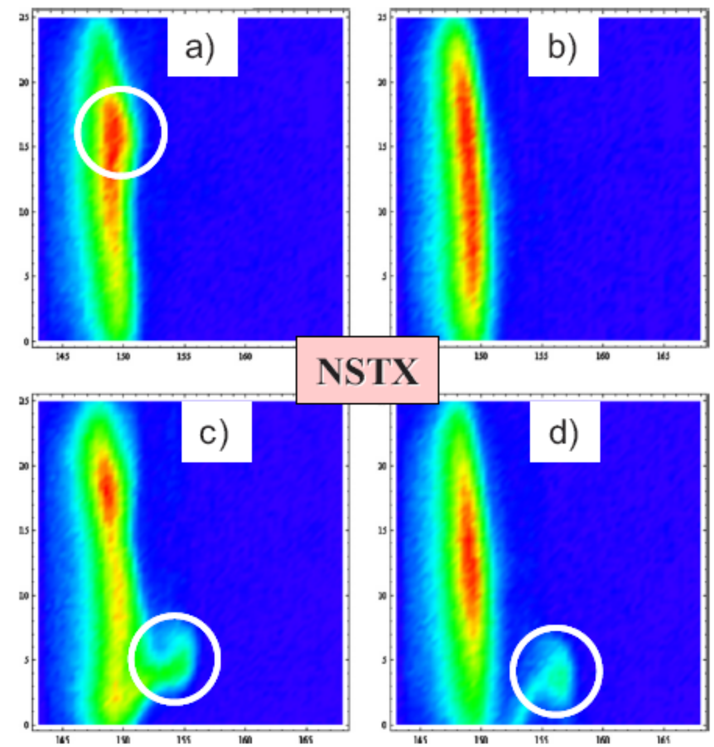
NSTX GPI Simulation in SOLT

SOLT simulations can produce qualitatively similar blob structures to those seen in GPI data (simulation results are for a synthetic GPI)

SOLT



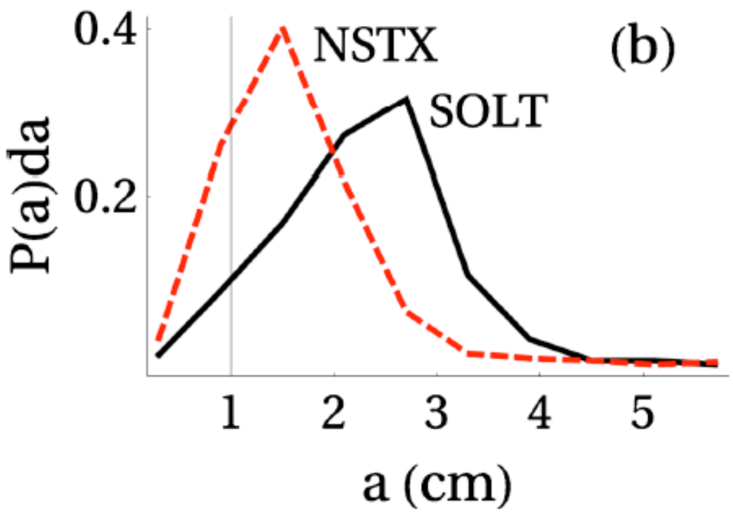
NSTX GPI

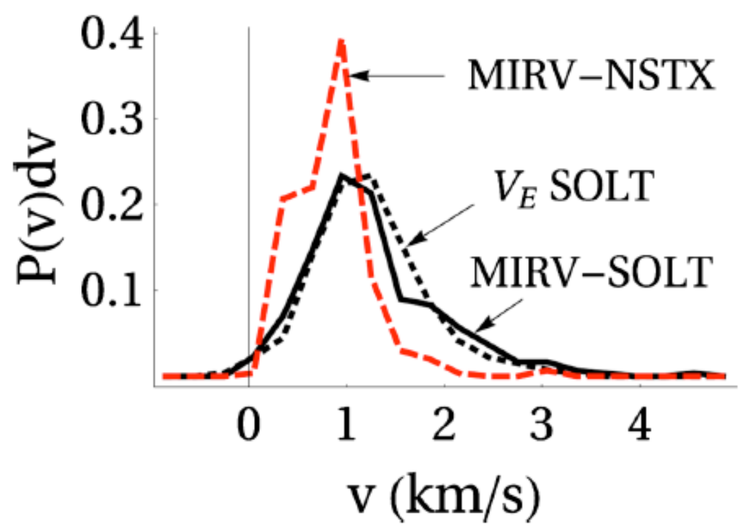


“Reduced model simulations of the scrape-off-layer heat-flux width and comparison with experiment”, J.R. Myra et al., Phys. Plasmas 18, 012305 (2011)

Blob Size and Radial Velocity Distributions

For OH and L-mode plasmas, typical SOLT code simulations give rough factor-of-two agreement in blob sizes (left) and V_{rad} (right) when both are passed through the same analysis stream

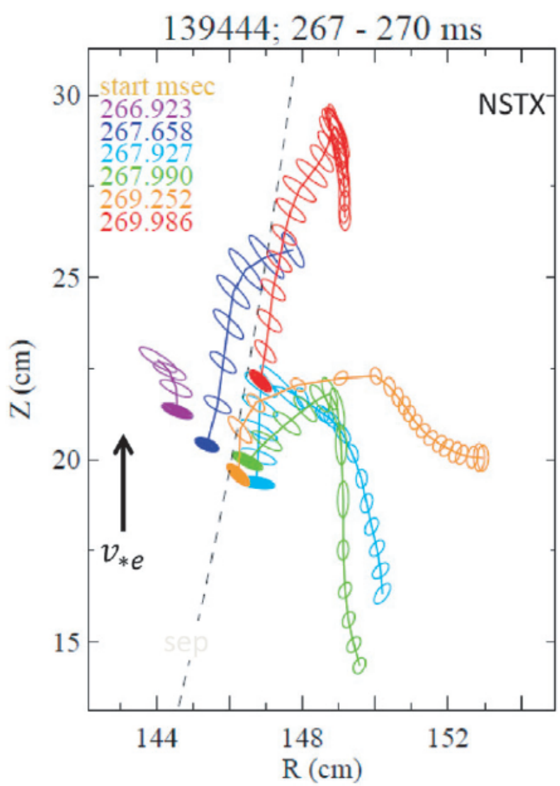


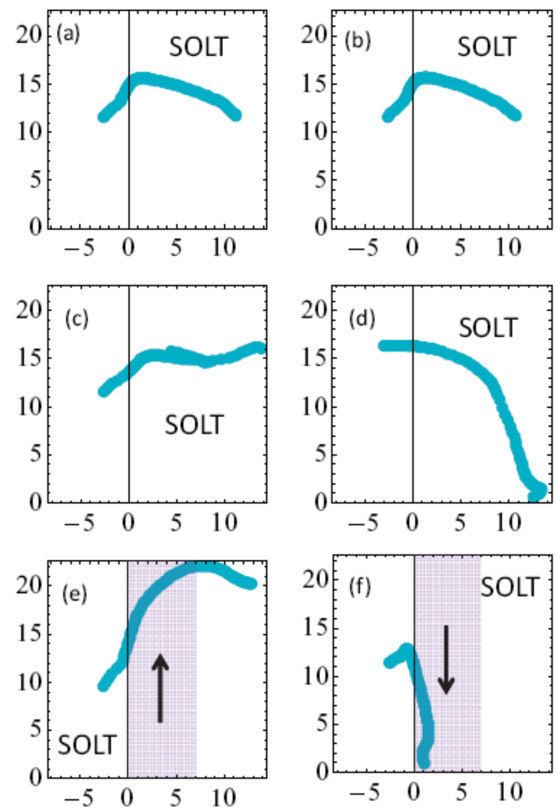


"Comparison of scrape-off layer turbulence simulations with experiments using a synthetic gas puff imaging diagnostic", D.A. Russell et al. Phys. Plasmas 18, 022306 (2011)

Blob Motion in the Radial-Poloidal Plane

The radial vs. poloidal motion of blob tracks seen in an NSTX Ohmic shot can be reproduced in "seeded" SOLT blob simulations



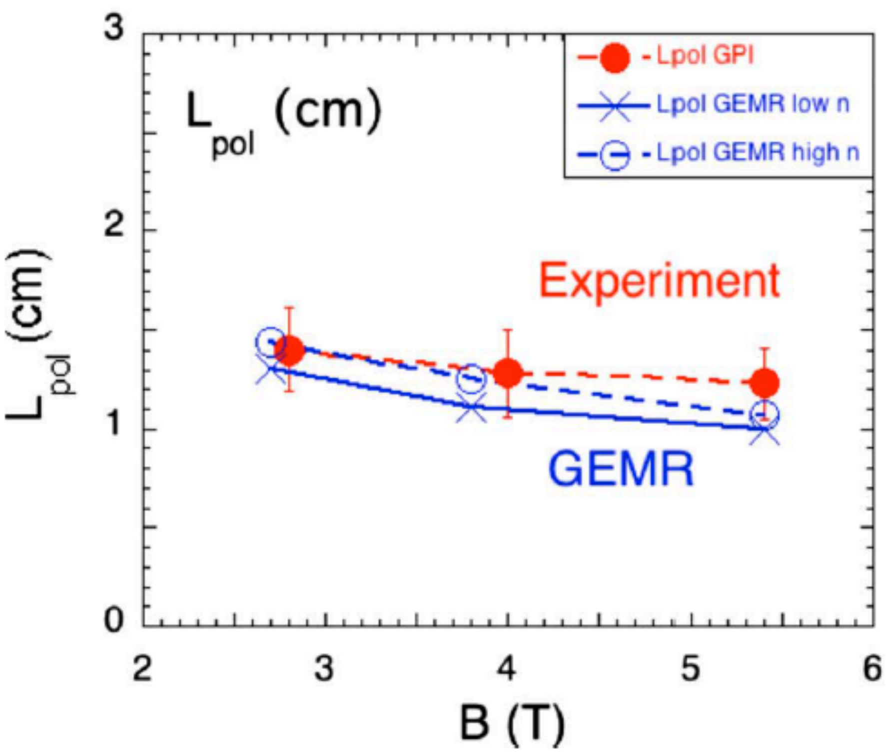


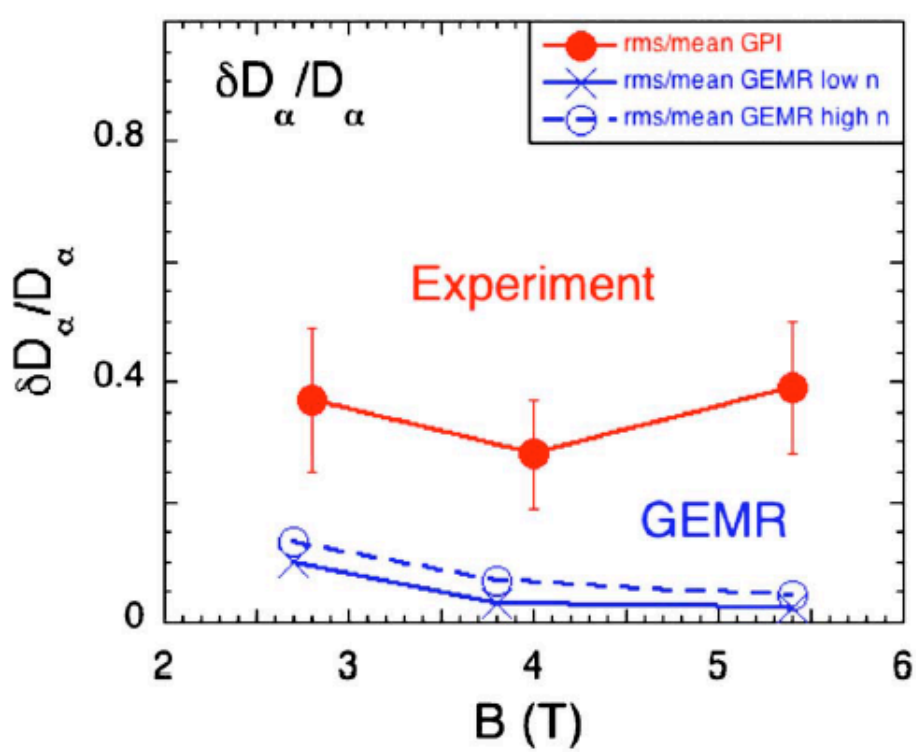
various assumed sheath conditions, adiabaticity, drifts, and SOL flows

"Edge sheared flows and the dynamics of blob-filaments",
J.R. Myra et al. Nucl. Fusion 53 (2013) 073013

Comparison of C-Mod GPI with GEMR

- GEMR is a 3-D electromagnetic (δ-f) gyrofluid code for SOL
- Six GEMR simulations done for circular Ohmic C-Mod shots, with a synthetic diagnostic for comparison with GPI data

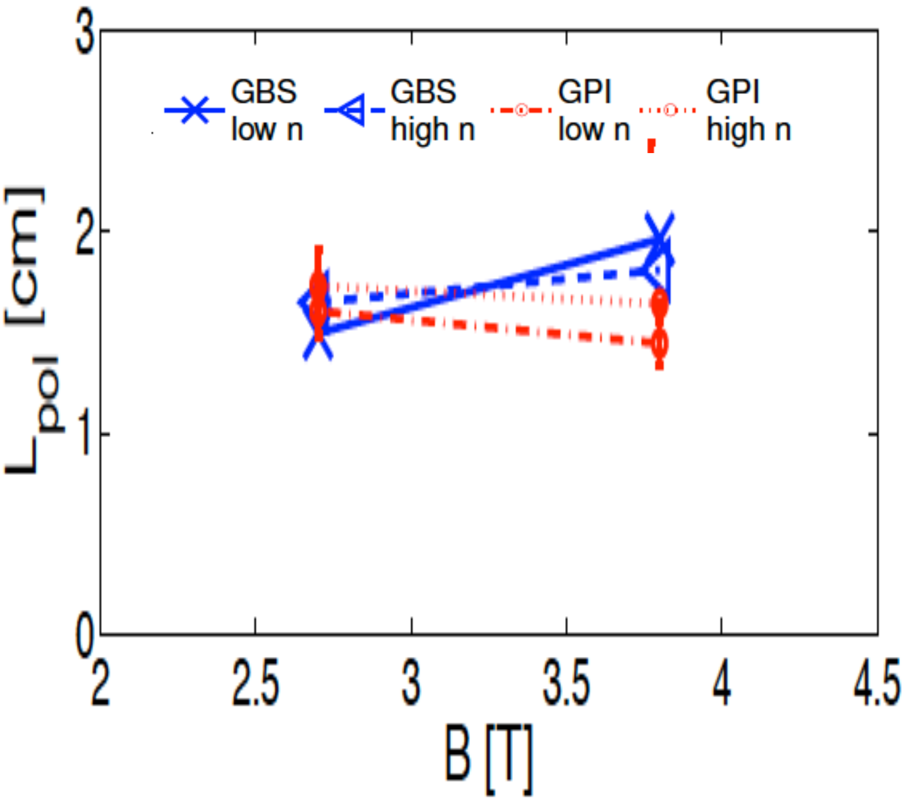


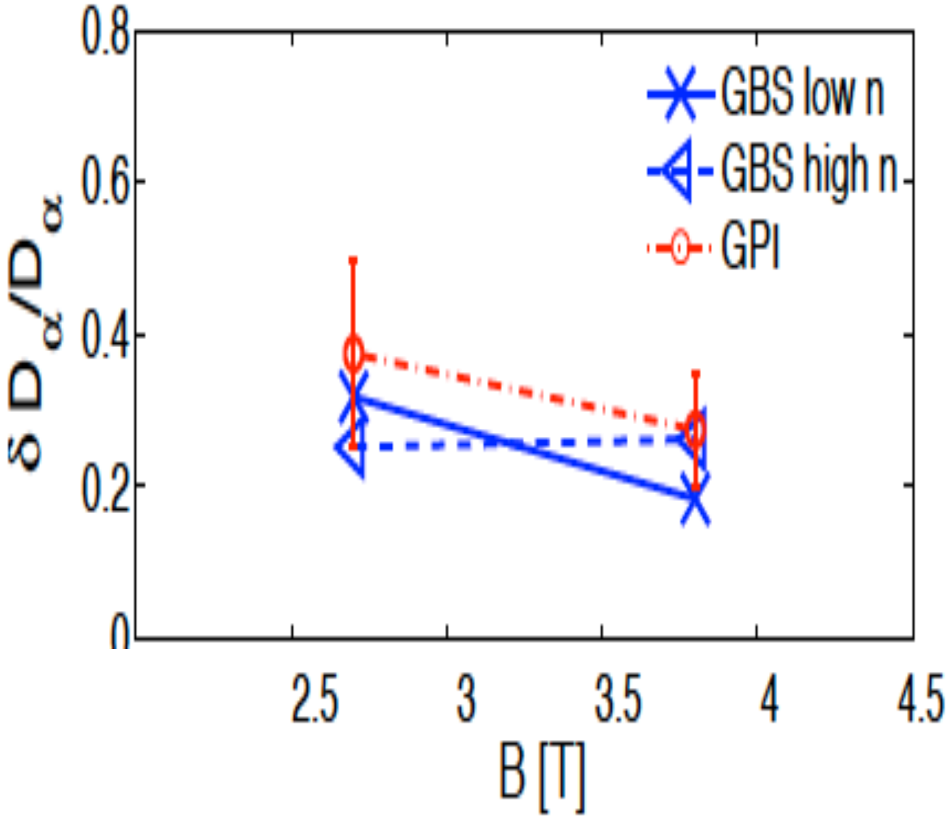


S.J. Zweben, B.D. Scott, J.L. Terry et al, Phys. Plasmas 16, 082505 (2009)

Comparison of C-Mod GPI with GBS

- GBS is a 3-D electrostatic flux-driven fluid model of SOL
- Four GBS simulations done for circular Ohmic C-Mod shots, with a synthetic diagnostic for comparison with GPI data



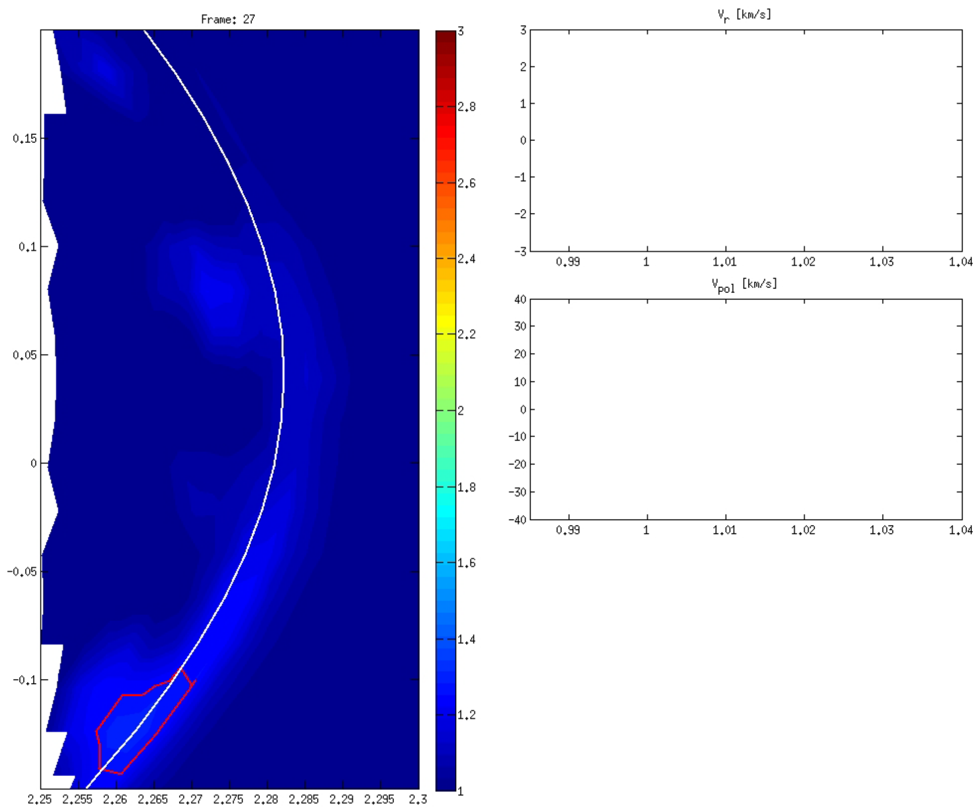


F.D. Halpern, J.L. Terry, S.J. Zweben et al, accepted in PPCF (2015)

Movie of XGC-1 Edge Turbulence in DIII-D

n_e/n_{eo}

4 μs/sec



blob Vrad vs. pol. flux

blob Vpol vs. pol. flux

M. Churchill, S. Ku, C.S. Chang

Suggested Directions for Simulations

- Compare turbulence from code with the measured turbulence for a controlled scan of some parameter (not just one shot)

- Determine *minimum* set of physics needed to explain observed turbulence to within the experimental uncertainty and/or day-to-day variation (somewhere between ~ 20% and x2)

- Determine sensitivity of simulation results to other parameters,
  e.g. how much do results change from ES to EM simulation ?
  e.g. how much does realistic impurity content affect results ?

- Do extensive benchmarking of codes against each other for standard cases which have turbulence measurements