Edge Turbulence Imaging in NSTX

S.J. Zweben, R.J. Maqueda, T. Munsat, D. Stotler,
C. Bush, B. Leblanc, R. Maingi
and the NSTX Team

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- Motivations and Background
- Gas puff imaging diagnostic
- Images from NSTX
- L-H transition in NSTX

Motivations

- Edge turbulence probably determines edge and SOL parameters, which can strongly affect the global confinement and plasma-wall interactions

- Edge turbulence can probably be understood from first principles by comparing turbulence data with theory (both simulations and simplified physics models)

Some topics of interest:

- Coherent structures
- Intermittency
- SOL transport
- L-H transition
- Shear and zonal flows
- Edge localized modes
- Quasi-coherent modes
- Density limit

What is Plasma Turbulence ?

- "Turbulence" is any random-looking plasma fluctuation
  - generally small scale compared to plasma size
  - generally associated with cross-B-field transport
  - more complex than fluid turbulence (B, E, ñ, etc)

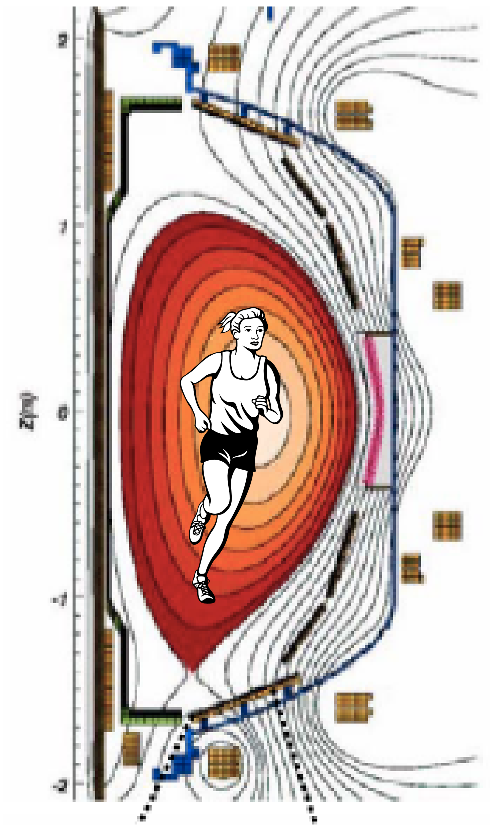
- Each linear instability can have a turbulent steady-state
  - drift wave turbulence, ion acoustic turbulence, etc.
  - usually takes only $\approx 10/\gamma$ to become turbulent
  - often little relation of turbulence to linear instability

- Essentially all real plasmas have some turbulence
  - fusion plasmas (magnetic, laser, even Q-machines)
  - industrial (arcs, thrusters, plasma processors, etc)
  - most astrophysical, magnetospheric, solar plasmas

Brief History

- Bohm and others saw “hash” in arc plasmas (1940’s)
- Early fusion experiments reported turbulence (1950’s)
- First nonlinear theories of plasma turbulence (1960’s)
- Initial comparisons of experiment and theory (1970’s)
- Many measurements of turbulence in tokamaks (1980’s)
- Development of nonlinear drift wave simulations (1980’s)
- Comparison of nonlinear simulations w/experiment (1990’s -)

National Spherical Torus eXperiment



vol ~ 10 m^3

NSTX Parameters

$R = 0.85$

$a = 0.68$

$B = 0.4$ T

$I = 1$ MA

$P = 12$ MW

$T_e(0) \approx 2$ keV

$n_e(0) \approx 5 \times 10^{13}$ cm^{-3}

$\beta \leq 40\%$

$T_e(a) \approx 50$ keV

$n_e(a) \approx 1 \times 10^{13}$ cm^{-3}

Gas Puff Imaging Diagnostic

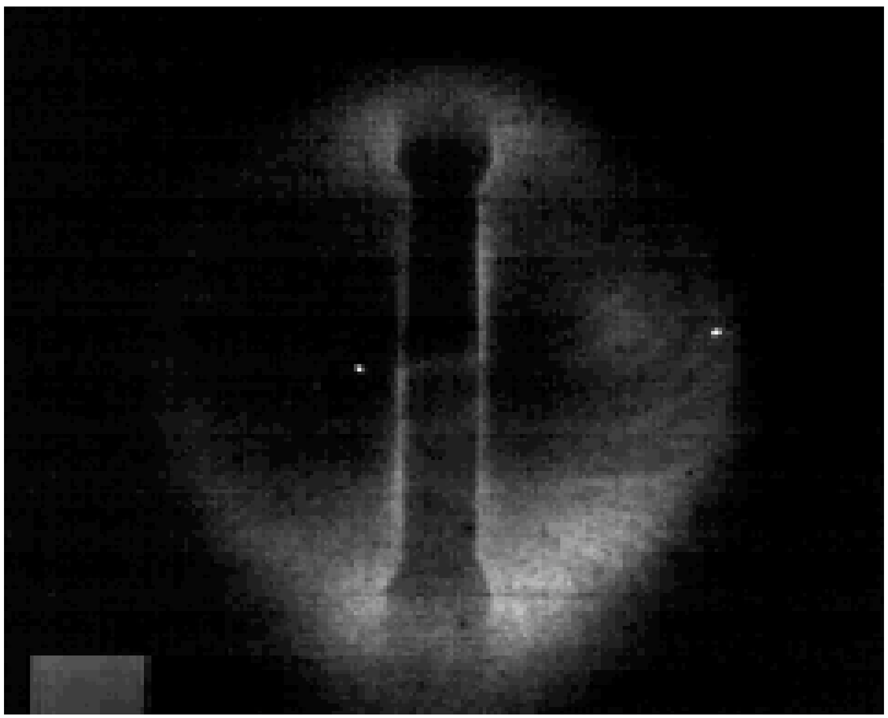
- High speed cameras see "filamentation" of D_α light emission (e.g. Niedermeyer, Goodall '82, TFTR '89)
- Fluctuations of D_α light similar to Langmuir probe results (e.g. Zweben '83, Endler '95)

=> GPI diagnostic in Alcator C-Mod and NSTX ('99 -):

- Image D_α light emission from a small gas puff
- View along B to see radial vs. poloidal structure

Turbulent "Filaments" in the Edge

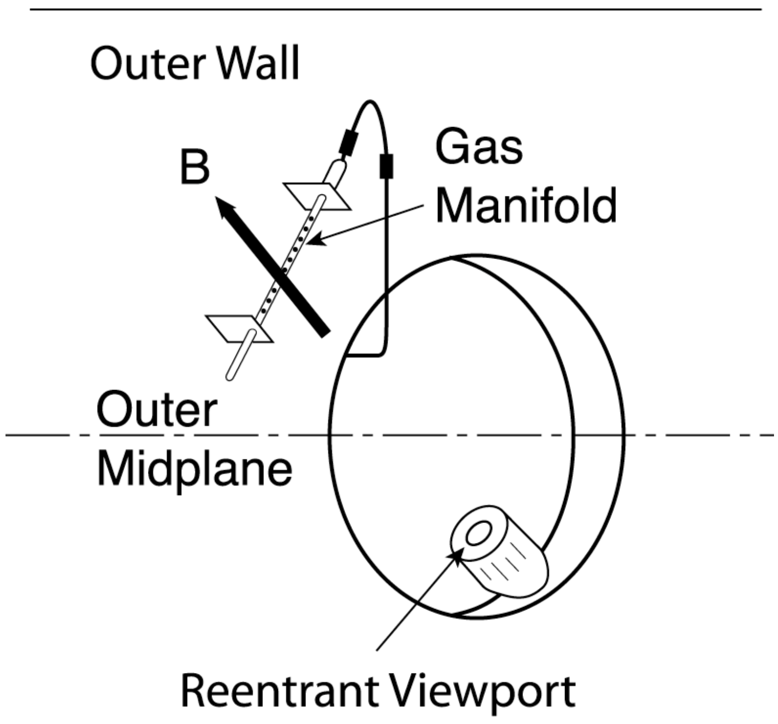
- These movies show the short poloidal correlation and long toroidal correlation length of the turbulence

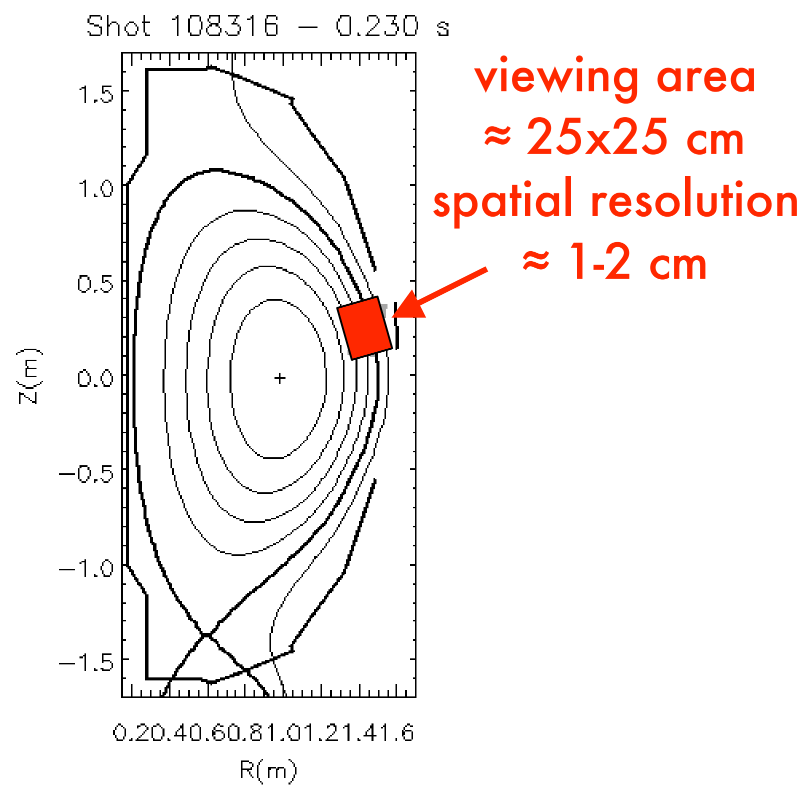


10 μsec/frame
1000 frames/sec
all visible light

GPI Diagnostic in NSTX

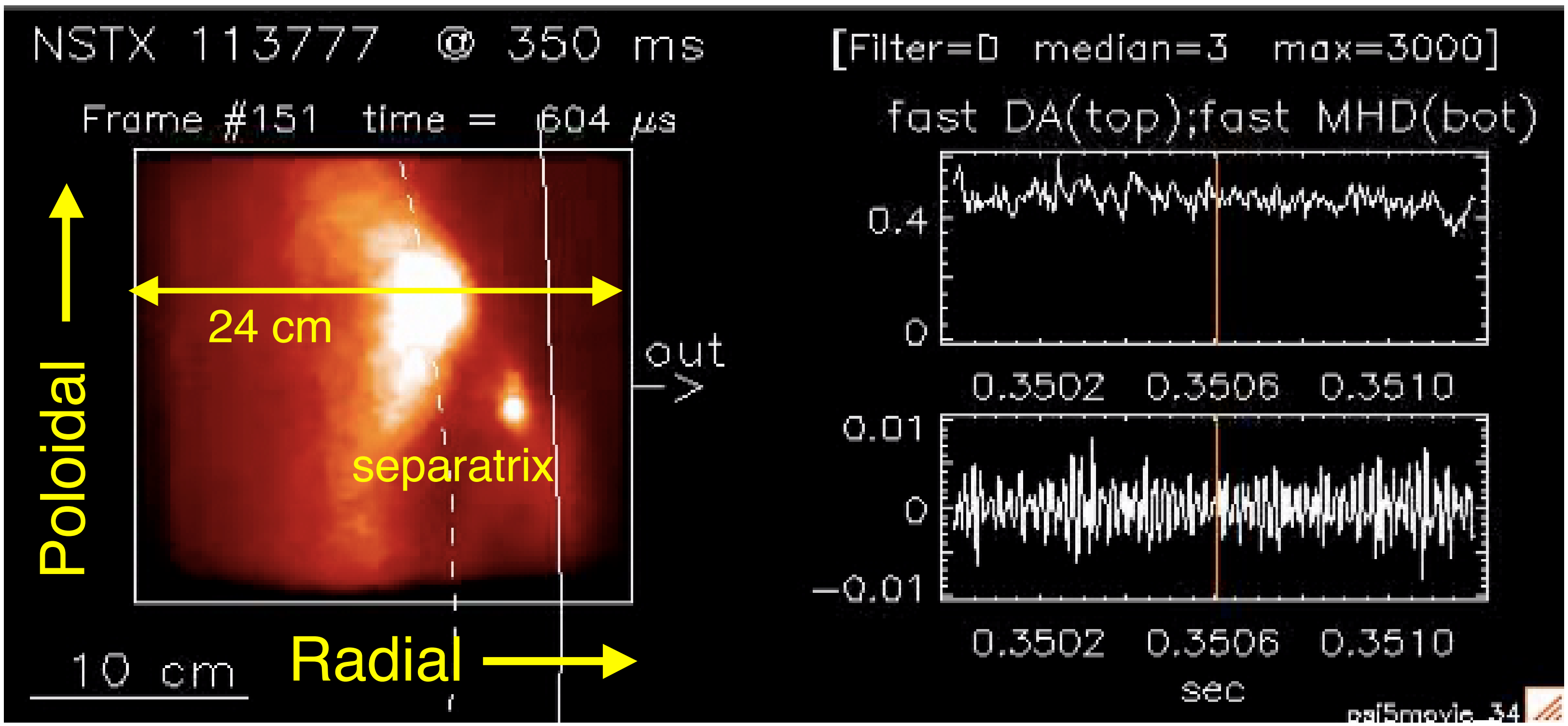
- Looks at D_α or HeI light from gas puff $I \propto n_o n_e f(n_e,T_e)$
- View ≈ along B field line to see 2-D structure ⊥ B
- Image coupled to camera with 800 x 1000 fiber bundle





GPI Data for NSTX ‘04 Run

- PSI-5 camera: 64x64 pixels, 250,000 frames/sec, intensified
- Also, discrete chords for longer time series at 13 points



see: http://www.pppl.gov/~szweben/NSTX04/NSTX_04.html

Ohmic Cases

Ohmic Plasma

NSTX #113348

B=4.0 kG, I=800 kA

<n>=2.4x10^{13} cm^{-3}

250,000 frames/sec

L-Mode Cases

NBI L-mode

NSTX #113830

B=3.0 kG, I=650 kA, 2.7 MW NBI

$\langle n \rangle = 3.3 \times 10^{13}$ cm^{-3}

250,000 frames/sec

H-Mode Cases

ELM-free H-mode

NSTX #113139

B=4.5 kG, I=825 kA, 0.9 MW NBI

250,000 frames/sec

Summary of NSTX Results

- Turbulence qualitatively similar in Ohmic and L-mode
  - size scale $\Delta_{pol} \approx 4$ cm, $\Delta_{rad} \approx 3$ cm
  - autocorrelation time $\tau \approx 30 - 70\ \mu$sec
  - light fluctuation level ≈ 20 - 80%
  - similar with LSN, USN, limited

- Edge plasma can be very quiescent during H-mode
  - quiet periods can last ≈ 10-100 msec
  - occasional “blobs” and coherent “waves”

- Frequency spectrum looks similar to Langmuir probe and edge reflectometer (at least, f ≤ 100 kHz)

Zweben et al, Nucl. Fus. ‘04

Questions for Image Analysis

- Are there patterns or structures in this turbulence ?
  - compare to blob theory & BOUT (e.g. Russell et al)
  - calculate statistical "mode-coupling" coefficients ?
  - try to match with simple dynamics (e.g. SOC, CA)

- Are there shear or zonal flows or radial streamers ?
  - calculate flow spectra from velocity maps
  - estimate vorticity, divergence, intermittency, etc.
  - compare with theory (e.g. Diamond, Hahm et al)

- Can turbulence be correlated with radial transport ?
  - roughly $D_\perp \sim \Delta^2/\tau \sim 10^5$ $cm^2/sec \sim D_{Bohm}$ ($> D_{nc}$?)
  - compare $\langle v_r \rangle_{turb}$ with $\langle v_r \rangle_{plasma} = \Gamma/n$
  - estimate $\Gamma = \langle n\, v_r \rangle$ directly from images ?

L-H Transition Cases

L-H Transition

NSTX #113079

B=4.4 kG, I=800 kA, 2.8 MW NBI

<n>=1.9×10^{13} cm^{-3}

250,000 frames/sec

Just Before L-H Transition

1 msec Before L-H Transition

NSTX #113735

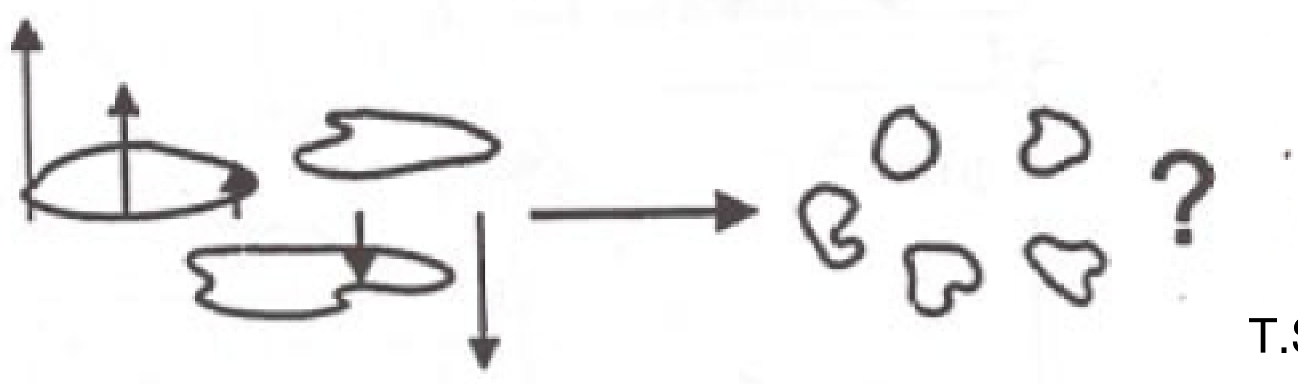
B=3.0 kG, I=790 kA, 4.4 MW NBI

$\langle n \rangle = 2.3 \times 10^{13}$ cm^{-3}

250,000 frames/sec

Analysis of L-H Transition

- Conventional model for L-H transition involves poloidal shearing of turbulence, leading to reduced transport

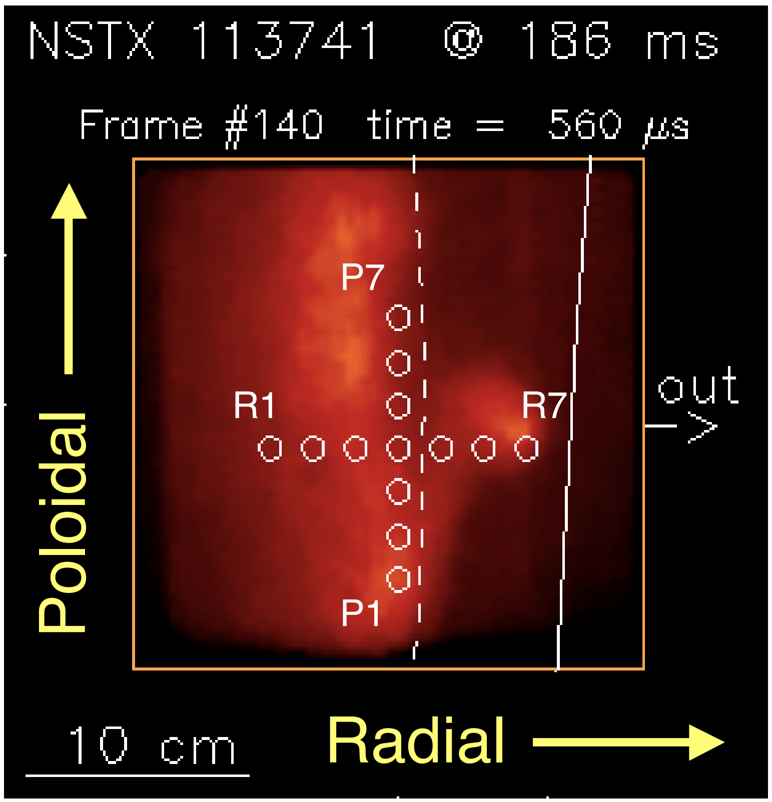


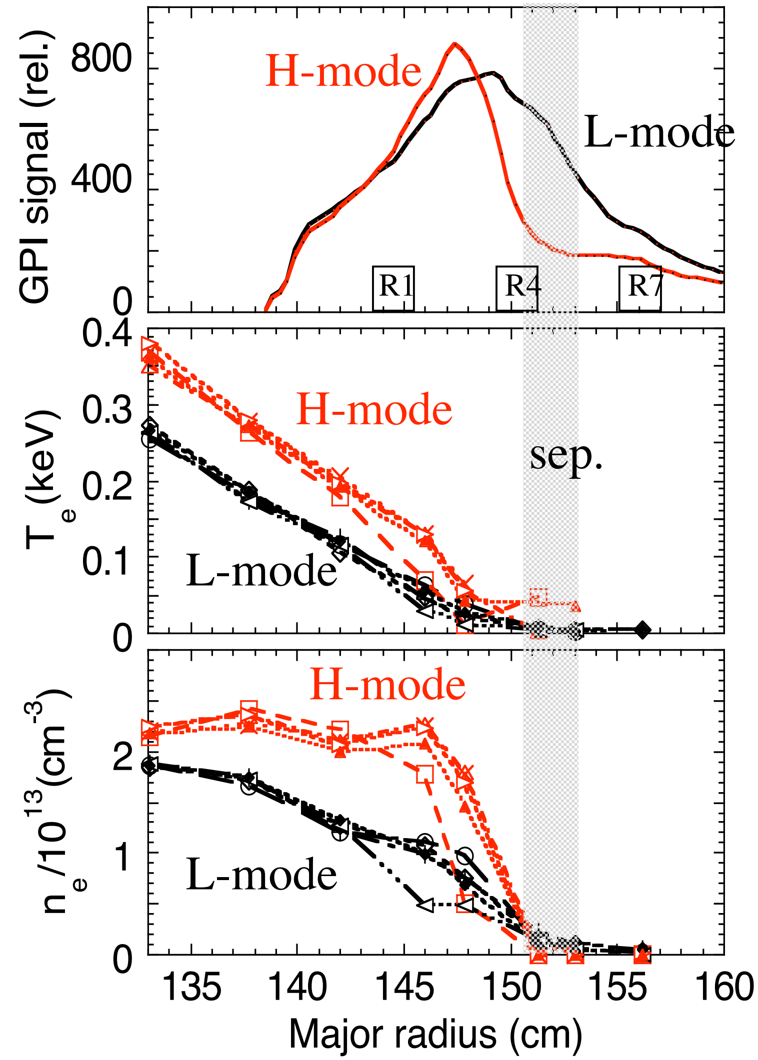
T.S. Hahm

Is this really happening in NSTX L-H transitions ?

- time series analysis of discrete chords (preliminary)
- 2-D image analysis for flows and patterns (not yet)

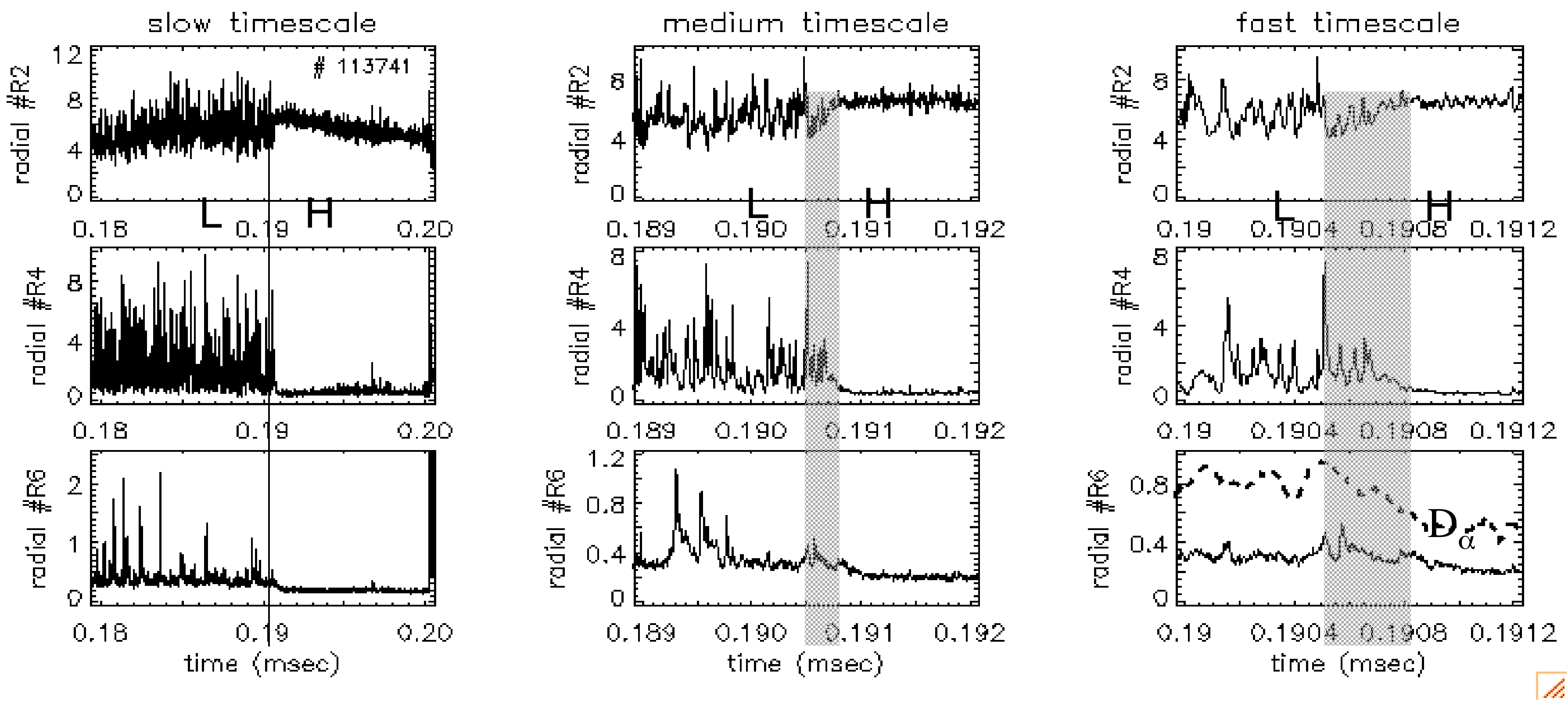
Discrete Chords within GPI Images





≈ 2 cm spatial resolution
≈ 200 kHz frequency resolution

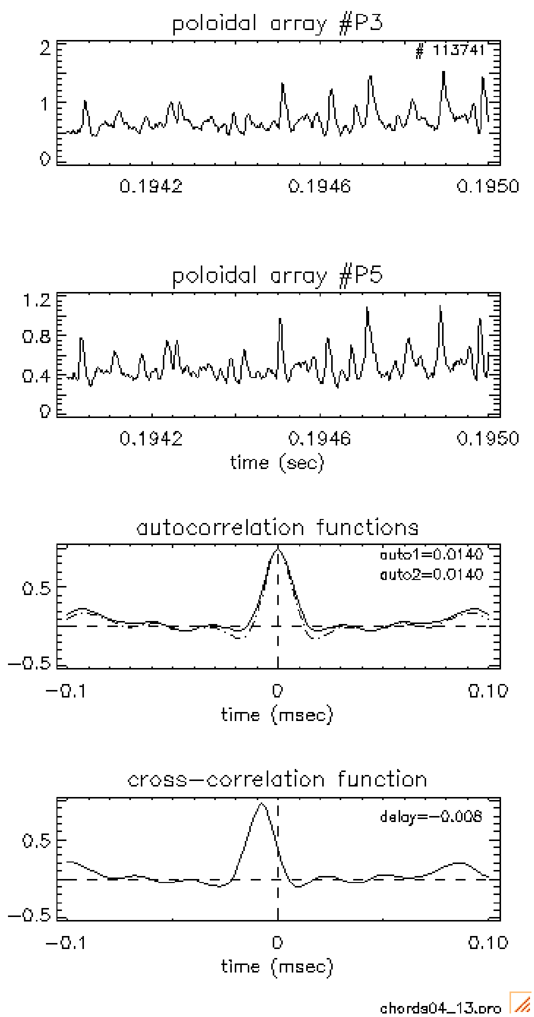
Time Dependence vs. Radius



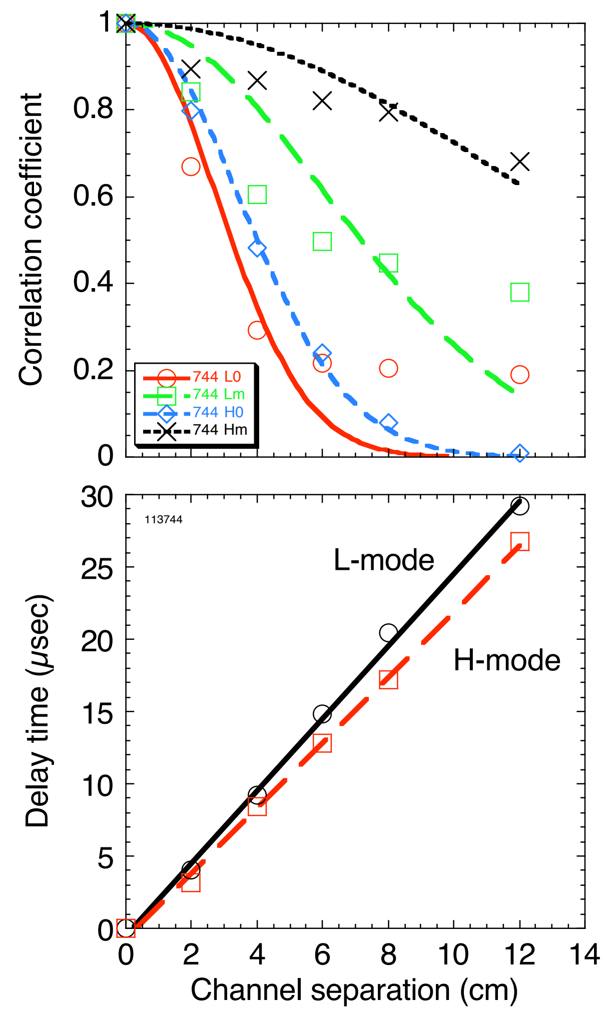
- Can see no changes in turbulence just before L-H transition
- Can’t hear any either

Example of Statistical Analysis

P3 vs. P5 (Δ = 4 cm)

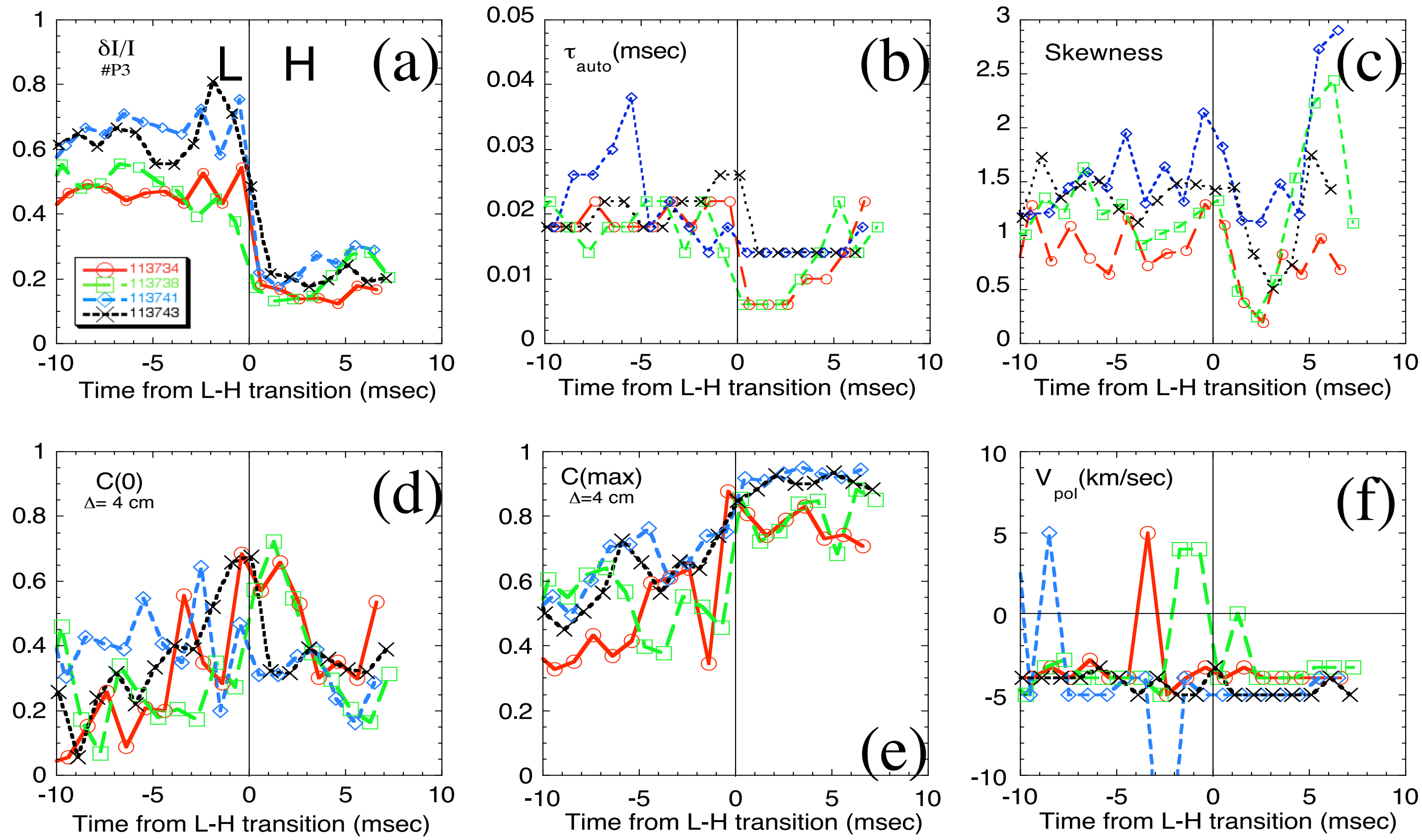


P1 vs. all other P's



Time Evolution at L-H Transition

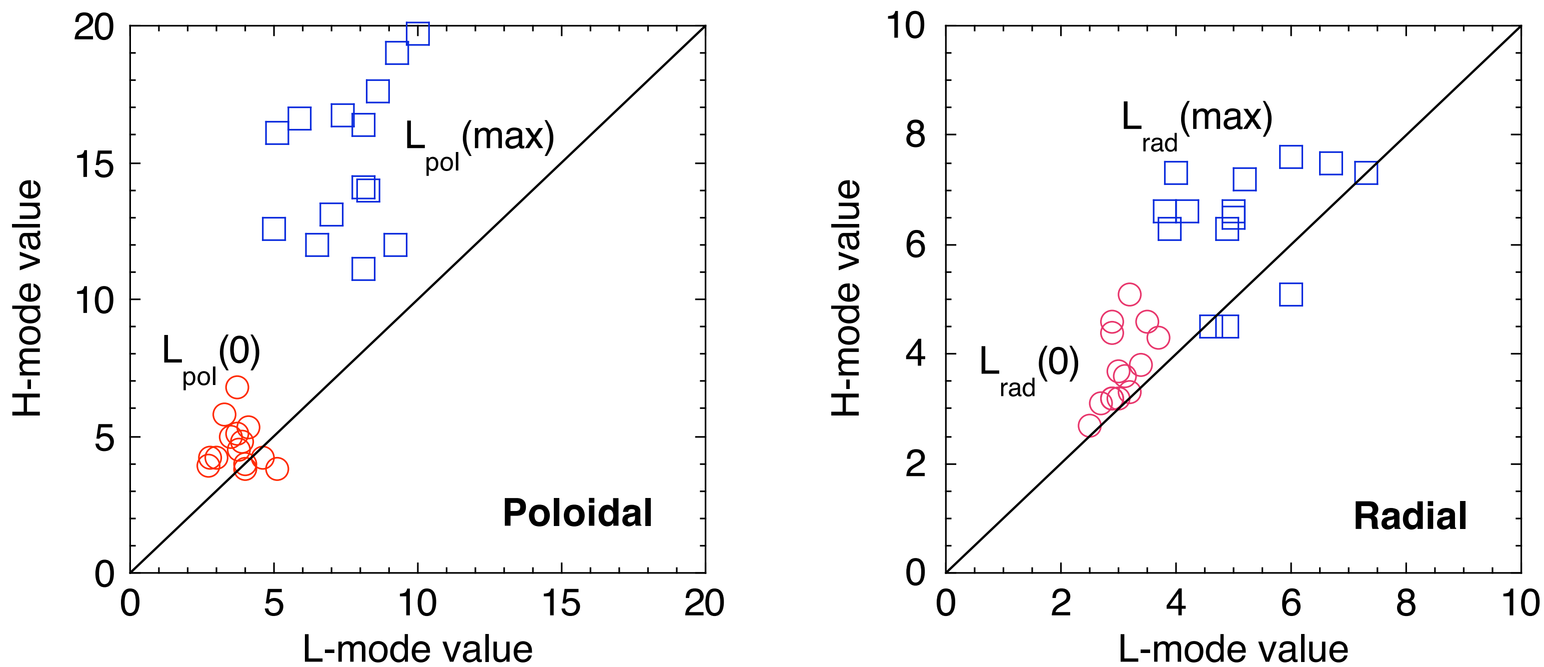
- Four shots from best data set (#113732-113744)



- Most surprising change is increase in C(max) from L to H

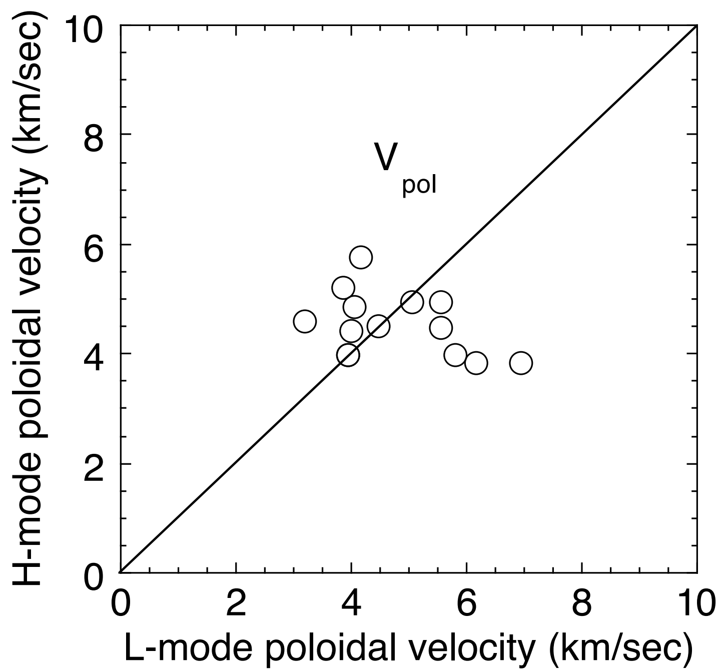
Correlation Lengths L vs. H

- Integrated over 5 msec before and after L-H transition



- Not much change in $L_{pol}(0)$ or $L_{rad}(0)$ from L to H

Poloidal Turbulence Velocity L vs. H



- No significant change in V_{pol} from L to H (at this radius)

=> H-mode turbulence flow looks more "frozen"

Summary

- Plasma turbulence is not yet well understood
  - simulations are hard to understand
  - but simple models may be misleading

- Turbulence imaging seems to be worthwhile
  - utilizes our innate visual processing ability
  - but quantitative analysis can be difficult

- One path to solve this problem:
  - compare different experiments (NSTX, C-Mod, TJ-II)
  - compare different codes (LLNL, Garching, Riso)
  - compare manyy experiments with many codes
  - understand codes using simple theory