GPI Masurements of Edge and SOL Turbulence Across the L-H transition in NSTX

A. L. Roquemore, S.J. Zweben, R.J. Maqueda[1], S. Kubota[2], T. Munsat[3], S. Kaye, R. Maingi[5], K.C. Lee[6], D. Stotler, K. Tritz, R. Bell, B.D. Scott[7], T.S. Hahm

PPPL, [1]Nova Photonics, [2]UCLA, [3]Colorado, ORNL [5], UC Davis, [6]IPP Garching[7]

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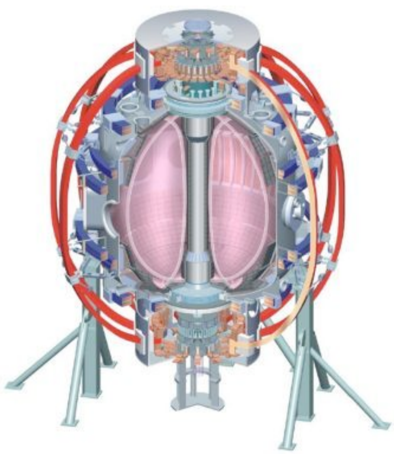

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Abstract

Edge turbulence across the L-H transition has been measured using the gas puff imaging (GPI) diagnostic over a 2-D region ~25 cm poloidal by ~25 cm radial at the outer midplane edge and scrape-off-layer (SOL) of NSTX. An improved GPI camera system is capable of imaging up to 285,000 frames/sec for over 50 msec at 4 μs/frame with a ~1 cm spatial resolution. The GPI system shows a clear reduction in the SOL turbulence fluctuation levels over a period ≤100 μs during the L-H transition. The cross-correlation data from the GPI diagnostic has been analyzed to determine the time- and space-dependent radial and poloidal correlation lengths L_r and L_p and flow speeds V_r and V_p across the transition.

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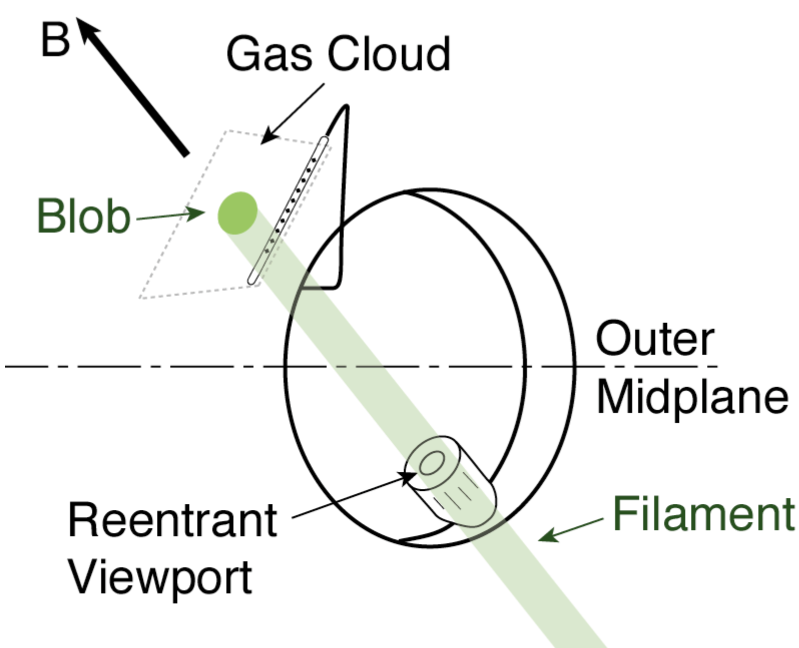
Outline of Poster

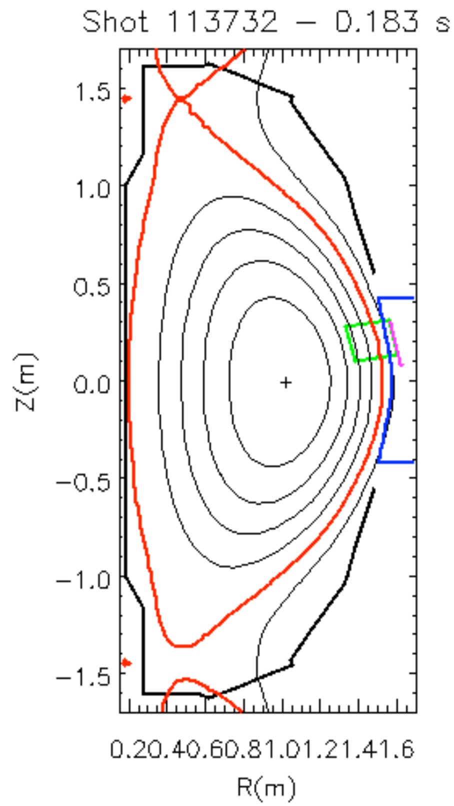
- Gas puff imaging (GPI) diagnostic on NSTX
- Examples of GPI images (movies)
- Fast dithers before the L-H transition
- Correlation analysis of turbulence
- Fine-scale velocimetry (Munsat)
- Wavelet bispectrum / bicoherence (Poli)
- Comparisons with other diagnostics (Kubota, Lee)

Gas Puff Imaging (GPI) Diagnostic

- Looks at D_α line of neutral deuterium from a gas puff
- View ≈ along B field line to see 2-D structure ⊥ B

view from center column





viewing area ≈ 25x25 cm
spatial resolution ≈ 1-2 cm

see: R.J. Maqueda et al, Rev. Sci. Inst. 2003

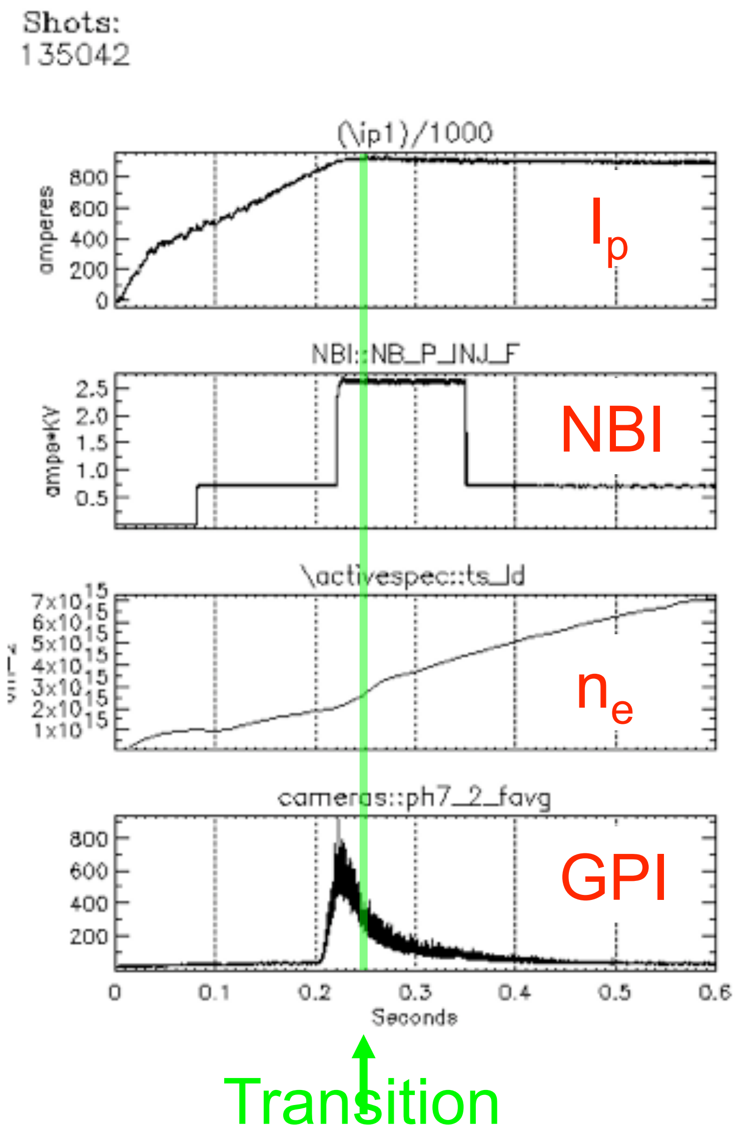
Interpretation of GPI Fluctuations

- Line emission signal levels $\propto n_e^{\alpha} T_e^{\beta}$ with $0.5 < \alpha, \beta < 2$, so measured signals are nonlinear functions of n and T_e [see Stotler et al, Cont. Plasma Phys. **44**, 294, 2004]

- However, turbulence structure and motion are approximately independent of these nonlinearities (~ "contrast knob") [see S.J. Zweben et al, Nucl. Fusion **44**, 134, 2004]

=> Assume that structure and motion of GPI light fluctuations represents structure and motion of the *turbulence* (not necessarily the same as the fluid motion)

Recent L-H Transition Experiment



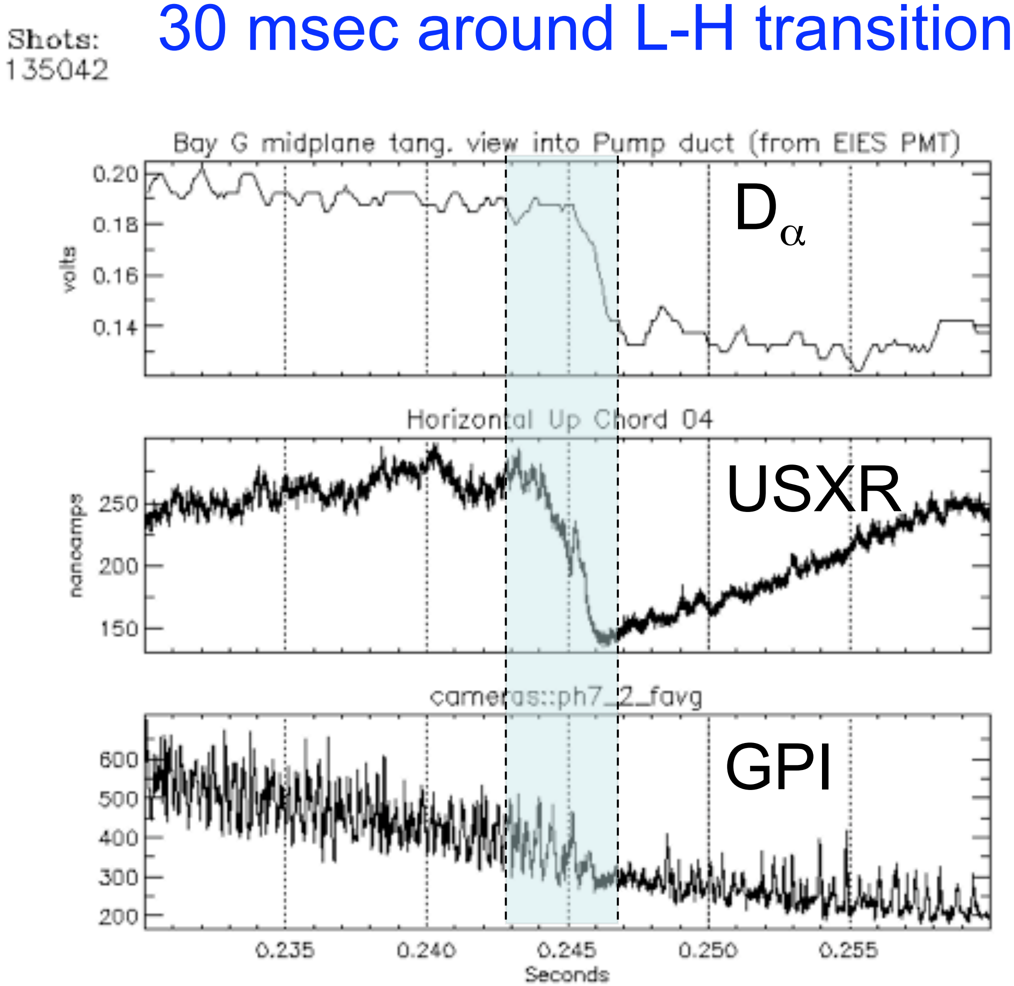
- Standard NSTX discharge
- Transition after added NBI
- Ultra-high speed GPI camera

  two Phantom 7.3 cameras viewing same image but interleaved in time

  => ~300,000 frames/sec in 64x64 pixel format

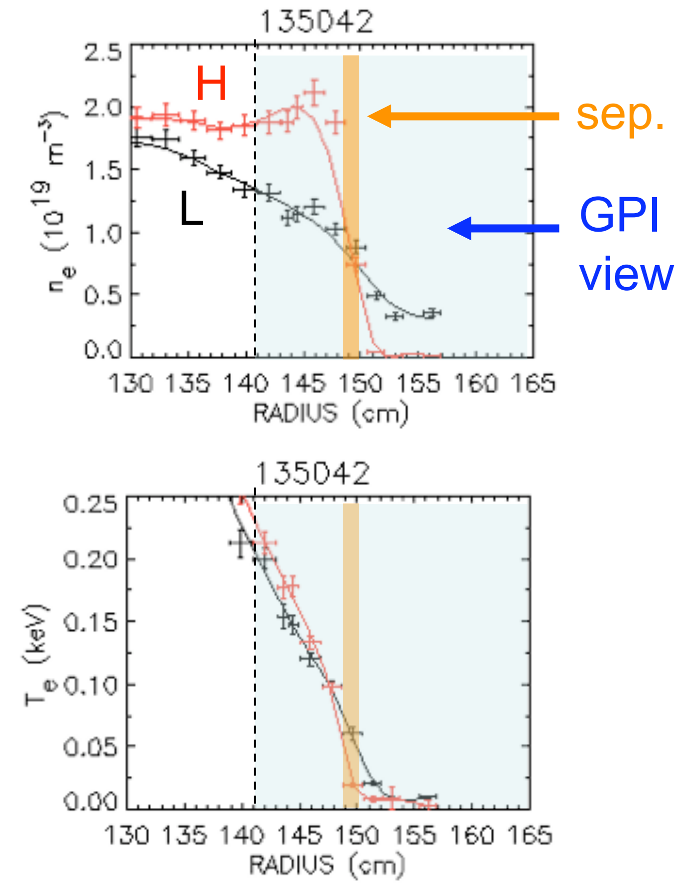
GPI location in Time and Space

30 msec around L-H transition



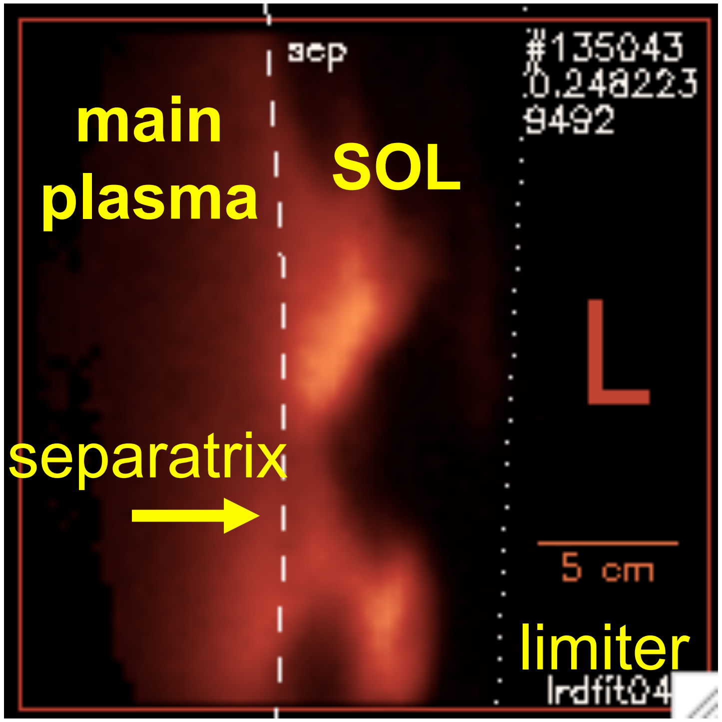
movie

Edge at transition

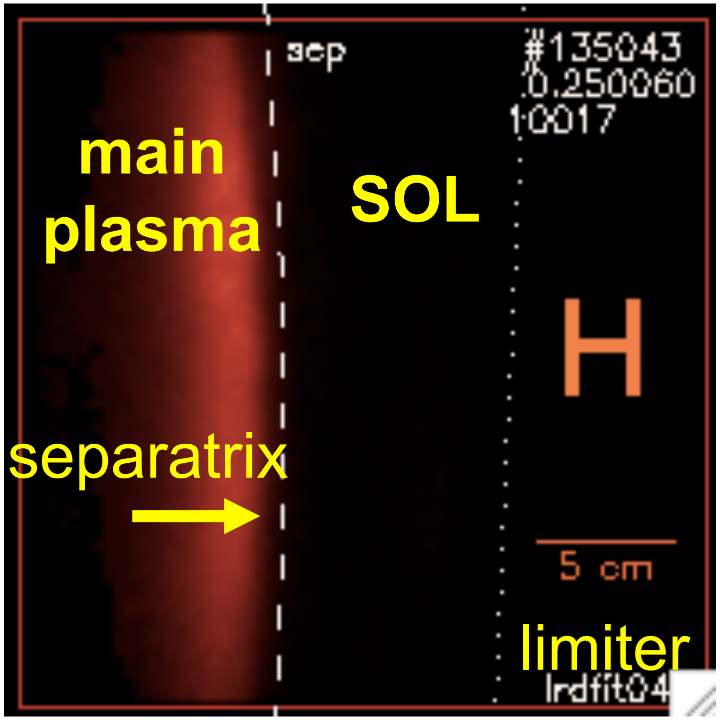


Examples of GPI Images from Movie

L-mode period



H-mode period



Examples of Images at L-H Transition

showing every third frame, i.e. @ 11 μs intervals

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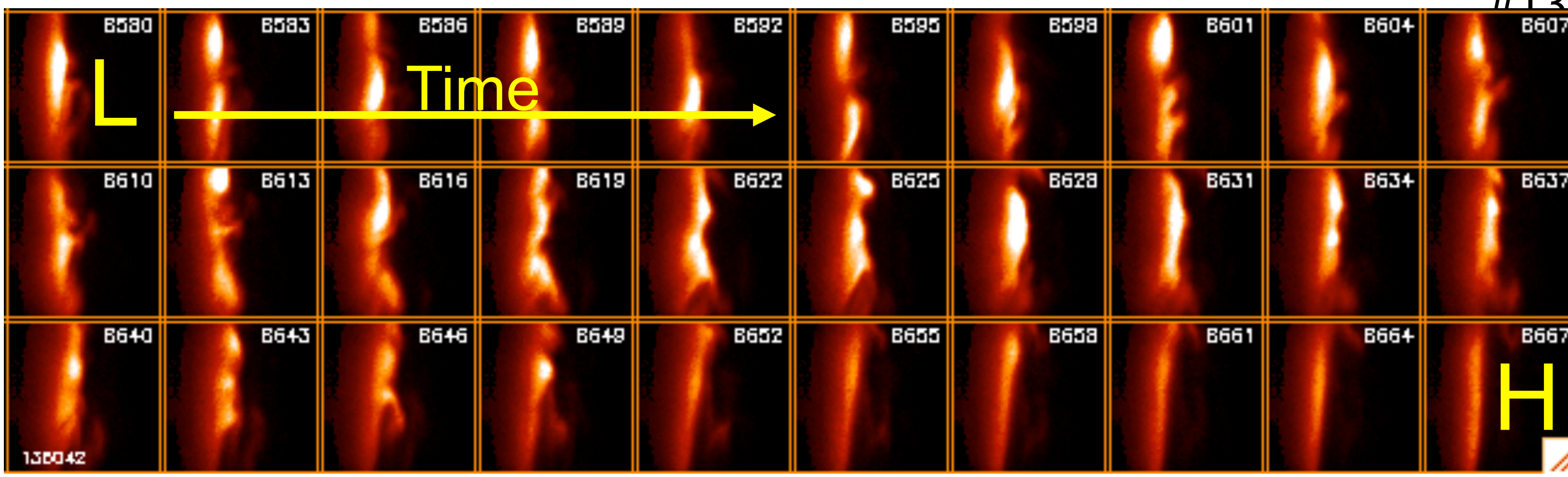

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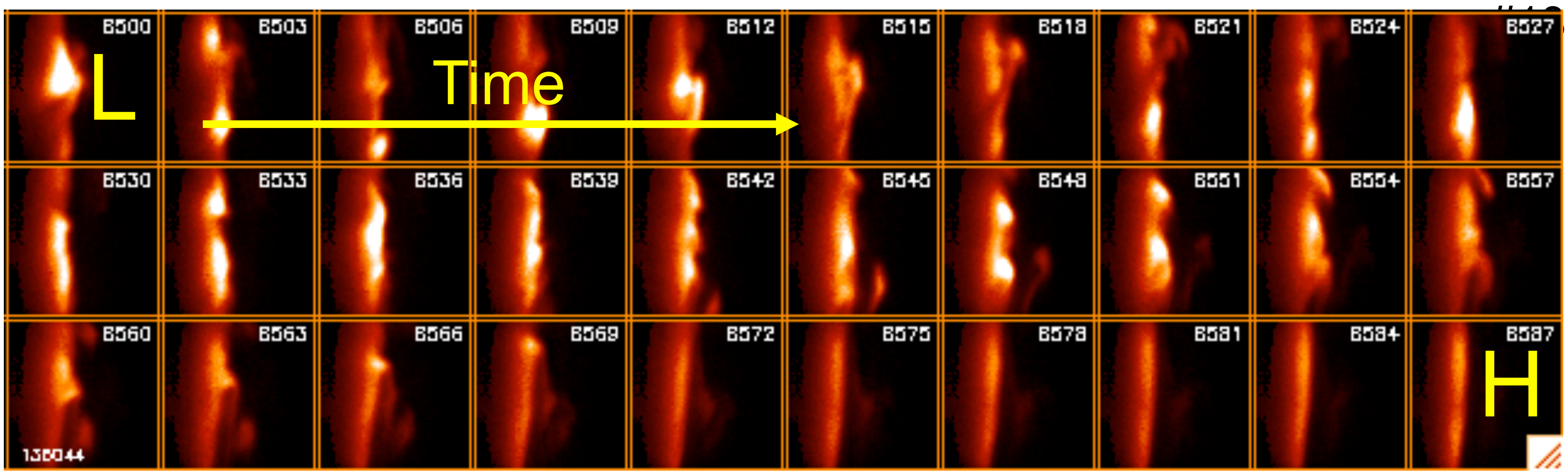

Fast Dithers Before L-H Transition

showing every third frame, i.e. @ 11 μs intervals

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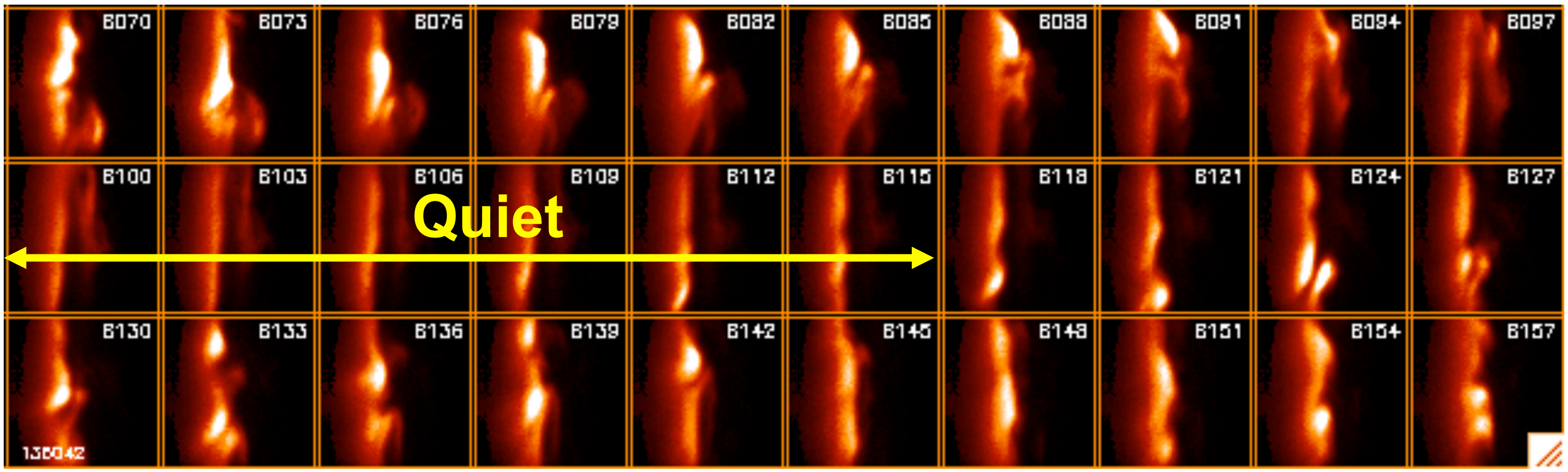
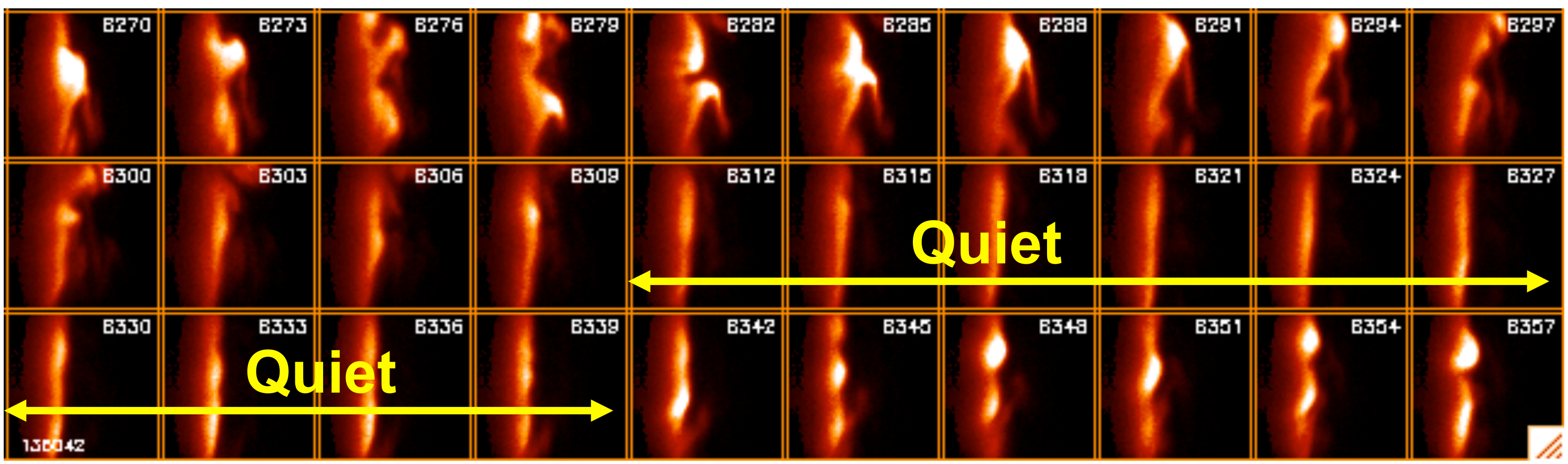
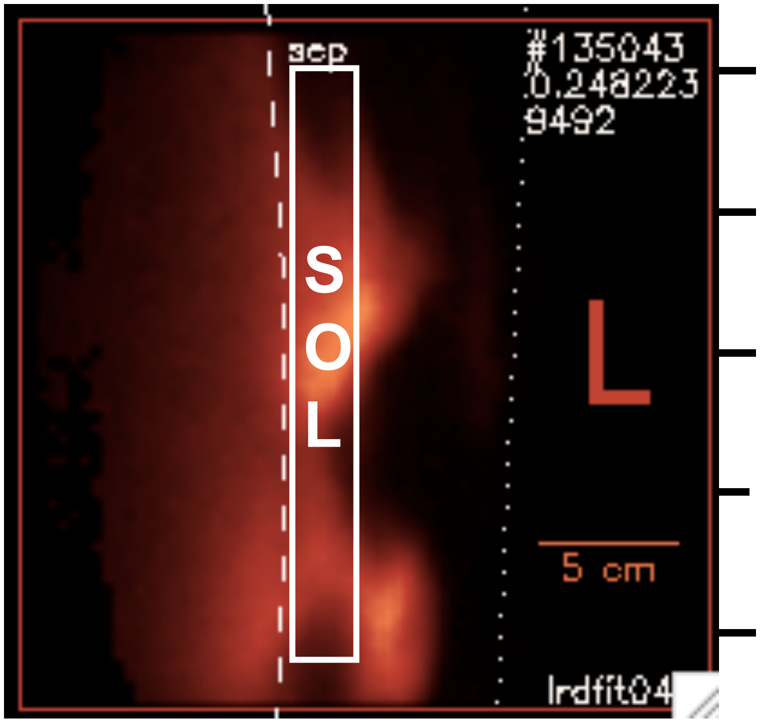
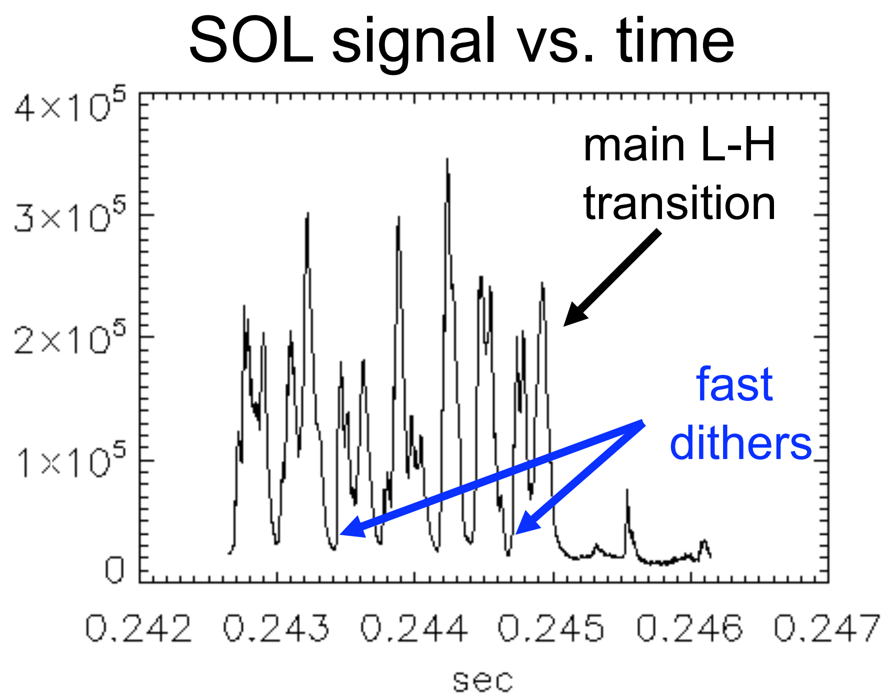




Fast Dithers Before L-H Transition





- Main L-H transition seen in GPI occurs over ~ 100 µs
- Note 6 fast dithers over ~2 msec before main transition

Correlation Analysis of Turbulence

- Use simple analysis via 2-point cross-correlation function of fluctuations in GPI light signals "S" vs. space and time:

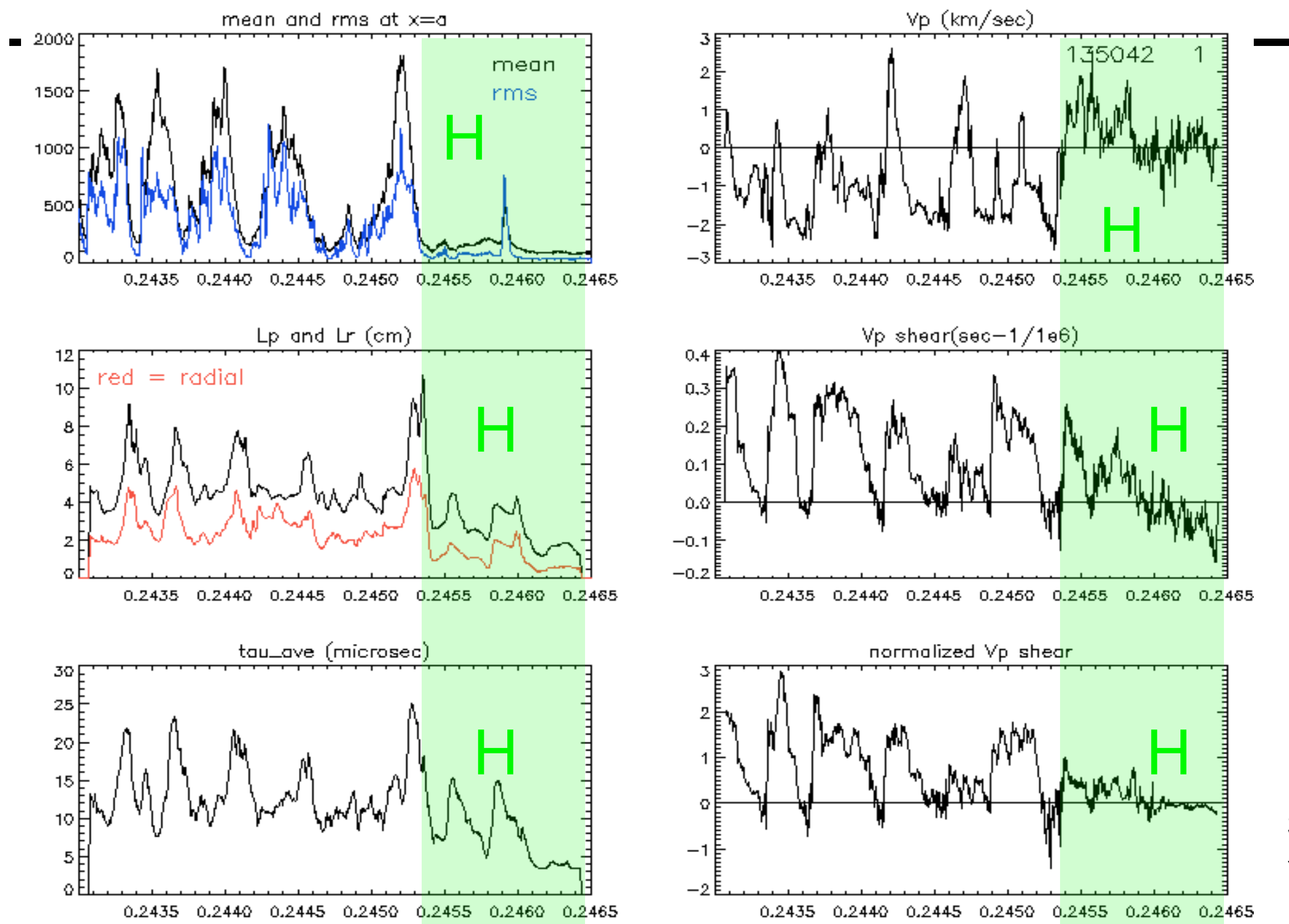
$$C(\Delta x, \Delta t) = \sum_{\text{time}} \tilde{S}_0(t)\, \tilde{S}_{\Delta x}(t+\Delta t)$$

- Correlation time from FWHM of $C(0,\Delta t)$ for each position
- Correlation length from FWHM of $C(\Delta x, 0)$ [$\approx 1.6 \times \sigma_{\text{Gaussian}}$]
- Turbulence velocity from 2D location of peak in $C(\Delta x, \Delta t)$

These are averaged over a chosen space and time range

Correlation Analysis vs. Time in SOL

- Some variations with fast dithering & small S/N in H-mode



mean
rms

L_p, L_r

τ_{auto}

V_p

∇V_p

norm. shear
$\nabla V_p (L_r/L_p)\tau$

time (sec)

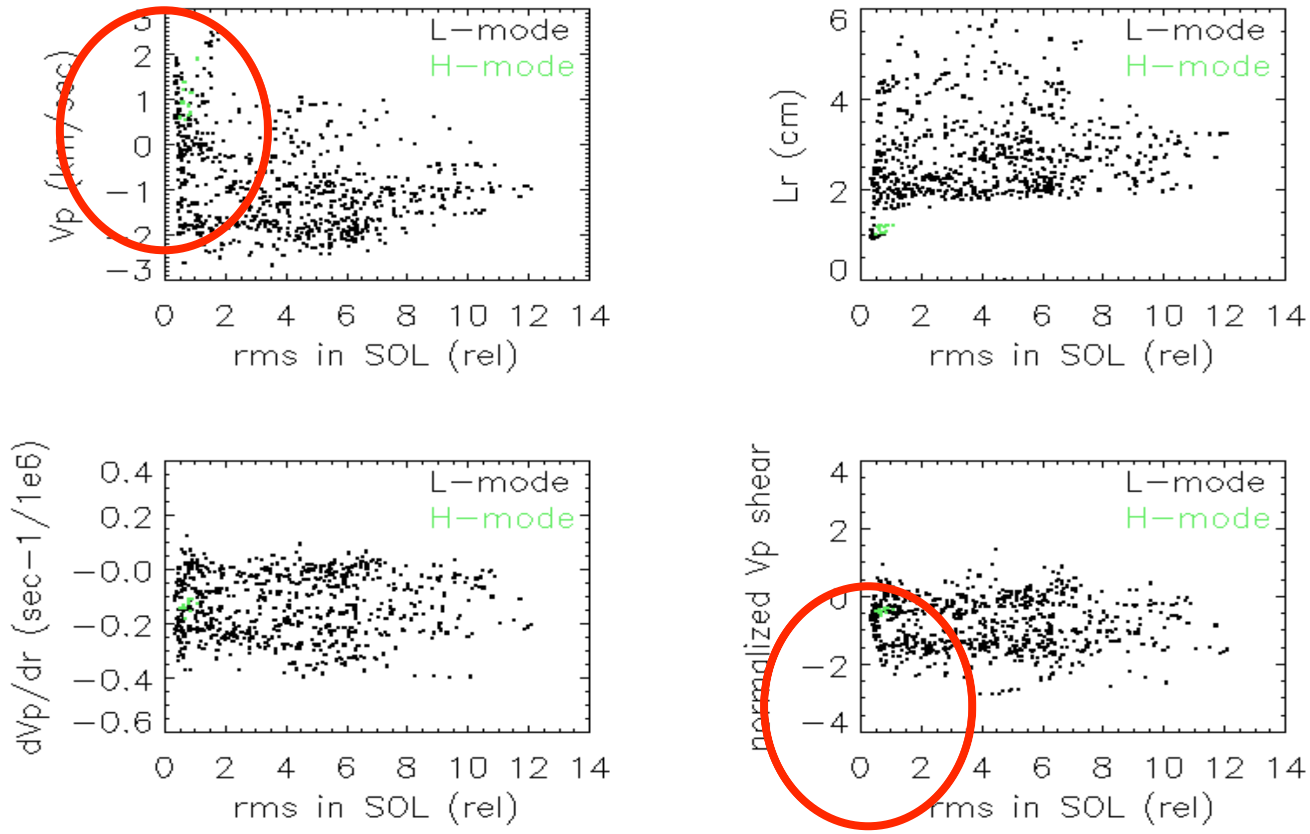
time (sec)

Shear vs. Fast Dithers in SOL

- Partial reversal of V_p direction during fast dithers in L-mode
- No clear change in normalized flow shear $\nabla V_p(L_r/L_p)\tau$

V_p

L_r



∇V_p

norm. shear $\nabla V_p(L_r/L_p)\tau$

Preliminary Results of Analysis

- Before L-H transition, H-mode-like fast dithers occur in SOL:
    - Occur at ~3 kHz for at least 20 msec before transition
    - Partial reversal of poloidal velocity at dithers (to EDD)
    - No clear change in turbulence correlation lengths
    - No clear change in normalized shear (~ 0 to 2)
- Just after L-H transition, GPI signal is very small in SOL
    - Probably due to reduction in density in SOL
    - Difficult to analyze SOL turbulence at this time

Analysis will continue...

Fine-Scale Velocimetry

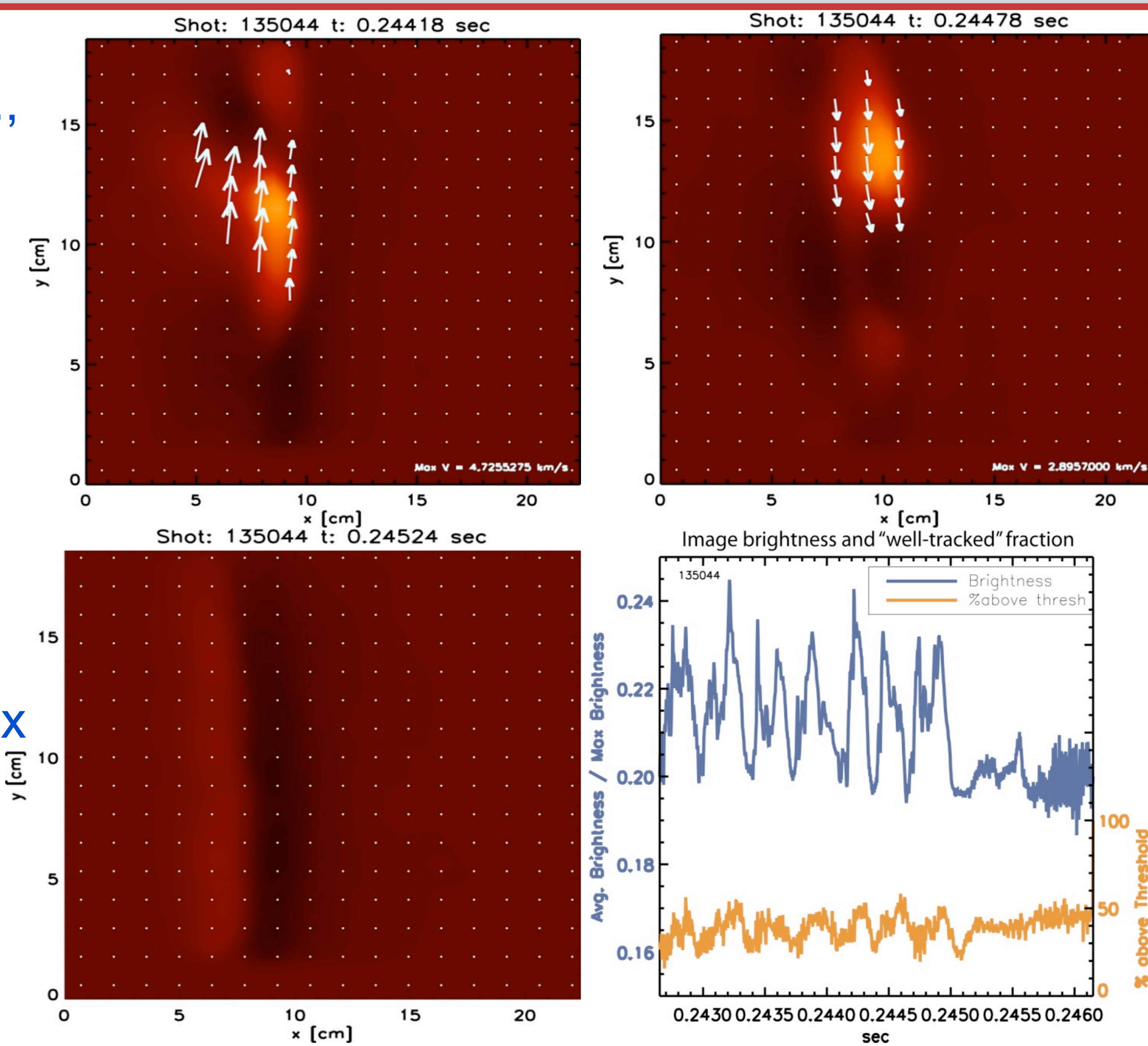
Y. Sechrest and T. Munsat, Univ. Colorado

- Combination of *Optical Flow* and *Direct Pattern Matching* techniques used to derive velocity fields from image frames *[Munsat and Zweben, RSI 2006]*
  - “Dense” flow fields
  - No a-priori knowledge of velocity behavior required
  - No a-priori knowledge of structures required
  - Analysis of turbulent flow fields possible
  - Techniques applicable to many diagnostic systems
  - Derive higher-order statistics from dense field maps
- “Thresholding” performed to eliminate vectors with low correlation (<0.9, representing poor tracking)

Typical Velocity Behavior of Structures

- L-mode: high curl (up one side of sep., down the other)
- H-mode: extremely quiet, with little velocity
- % of vectors above threshold fairly steady at ~40-50%

  Correlation > 90%, Intensity > .15 x max
- Brightness highly variable as blobs come and go

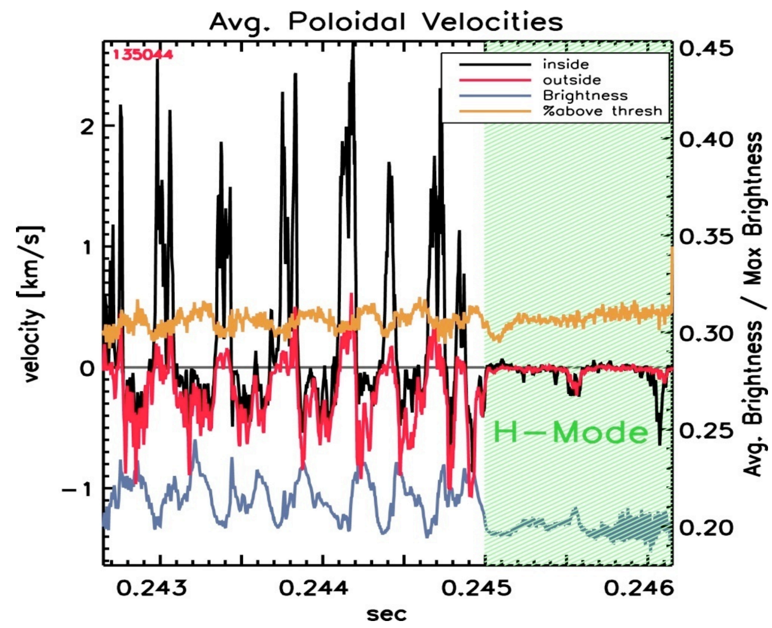


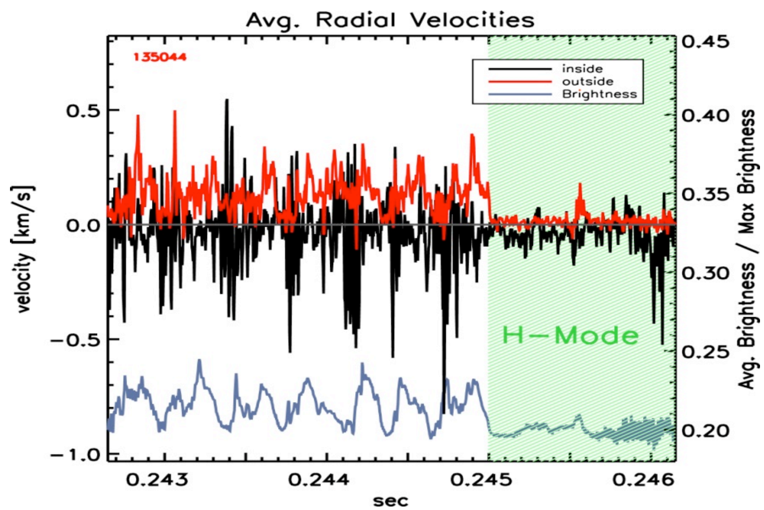
Poloidal and Radial Velocity vs. Time

- “Dithering” H-mode-like behavior highly visible in time-dependent velocity field maps
- Separate spatial averages (inside and outside separatrix) plotted vs. t
- Poloidal motion is highly intermittent; reverses during transition out of quiet/ H-mode periods
- Marked difference in V_{pol} inside and outside separatrix
- During *dim* periods, pronounced poloidal velocity inside separatrix (not fully H-mode quiet)

-- Blobs don’t cross separatrix and complete their normal trajector--

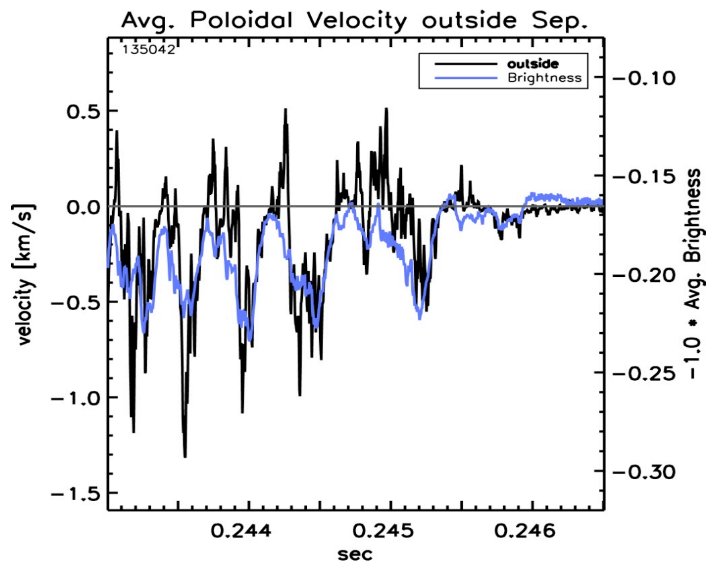
Almost no activity outside separatrix

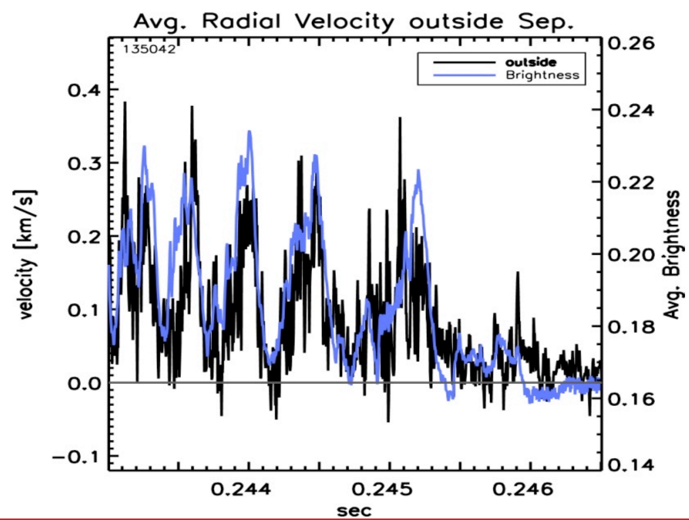




V-fields Closely Track Local Intensity

- Average brightness outside separatrix (renormalized, to show relative trends and direction) plotted with average poloidal and radial velocities
- High correlation between intensity of structures and their velocities
- Primary motion is poloidal
- Small radial (outward) velocity of traveling structures also consistent with intensity scaling





Wavelet Bispectrum / Bicoherence

F. Poli

$$B(\omega_l,\omega_m) = \frac{1}{M}\sum_{j=1}^{M} X_l^{(j)} X_m^{(j)} X_{l+m}^{*(j)}$$

The bispectrum characterizes 3-wave coupling

$$\omega_l + \omega_m = \omega_{l+m}$$

Resonance condition among frequencies

$$X_l = X_l(\omega) = \left|X_l\right| e^{i\alpha_l}$$

spectral components

$$b^2(\omega_l,\omega_m) = \frac{\left|B(\omega_l,\omega_m)\right|^2}{\left\langle \left|X_l X_m\right|^2 \right\rangle \left\langle \left|X_{l+m}\right|^2 \right\rangle}$$

bicoherence (normalized bispectrum)

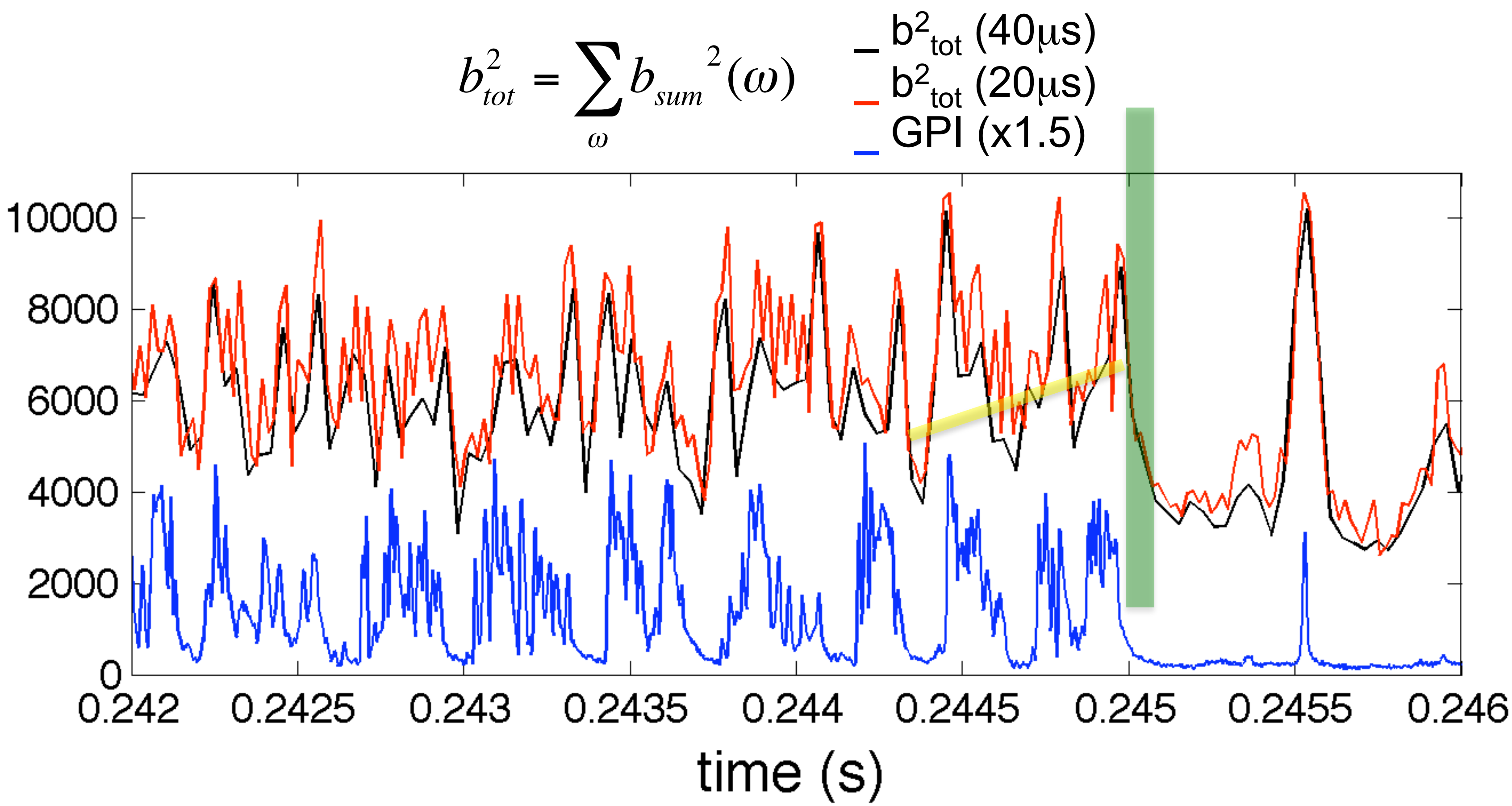
Average over many samples is needed for convergence of the bispectrum → Use the Morlet wavelet for computations of X, to increase statistics

$$\psi(t) = \frac{1}{\pi^{1/4}} e^{i\omega_0 t} e^{-t^2/2\sigma^2}$$

Sinusoidal function to extract the mode structure
Gaussian function for energy localization

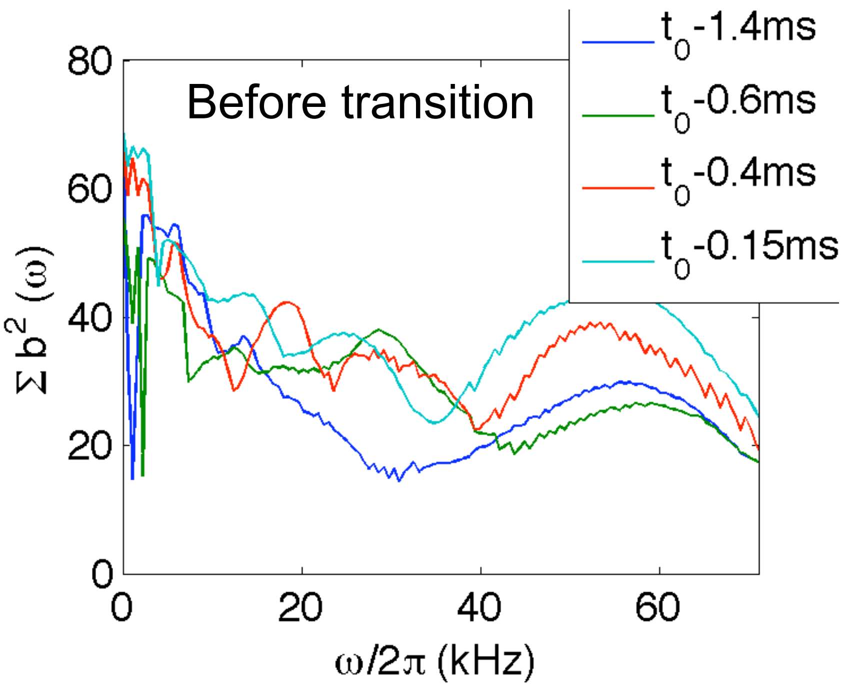
Moderate Increase in Nonlinear Coupling Before L-H Transition

$$b_{tot}^2 = \sum_{\omega} b_{sum}{}^2(\omega)$$



- the total bicoherence b^2_{tot} gives an indication of the level of nonlinear interaction in time
- b^2_{tot} increases ~25% during 0.5 ms prior to transition, during quiet periods (yellow line)
- drop in level of b^2_{tot} after the transition

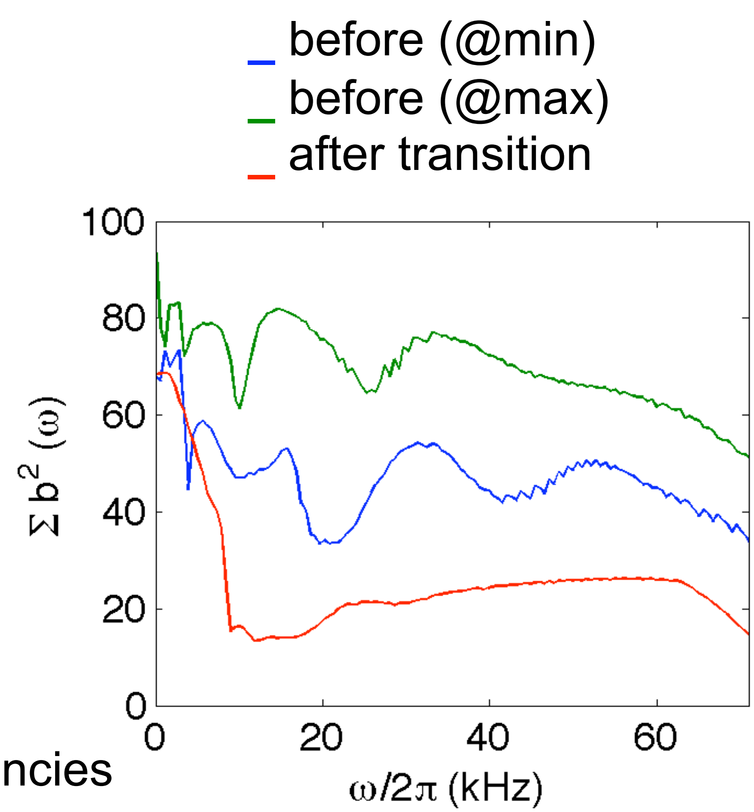
Change in the Character of Turbulence



Summed bicoherence

$$b_{sum}^{\;2}(\omega) = \sum_{\omega_l+\omega_m=\omega_{l+m}} b^2(\omega_l,\omega_m)$$

Average over 250 samples



Increased coupling at intermediate Frequencies before the transition. Work in progress on 2D data to assess range of scales involved.

Drop in coupling at intermediate frequencies. Residual coupling between low and high frequencies

Summary of Nonlinear Coupling

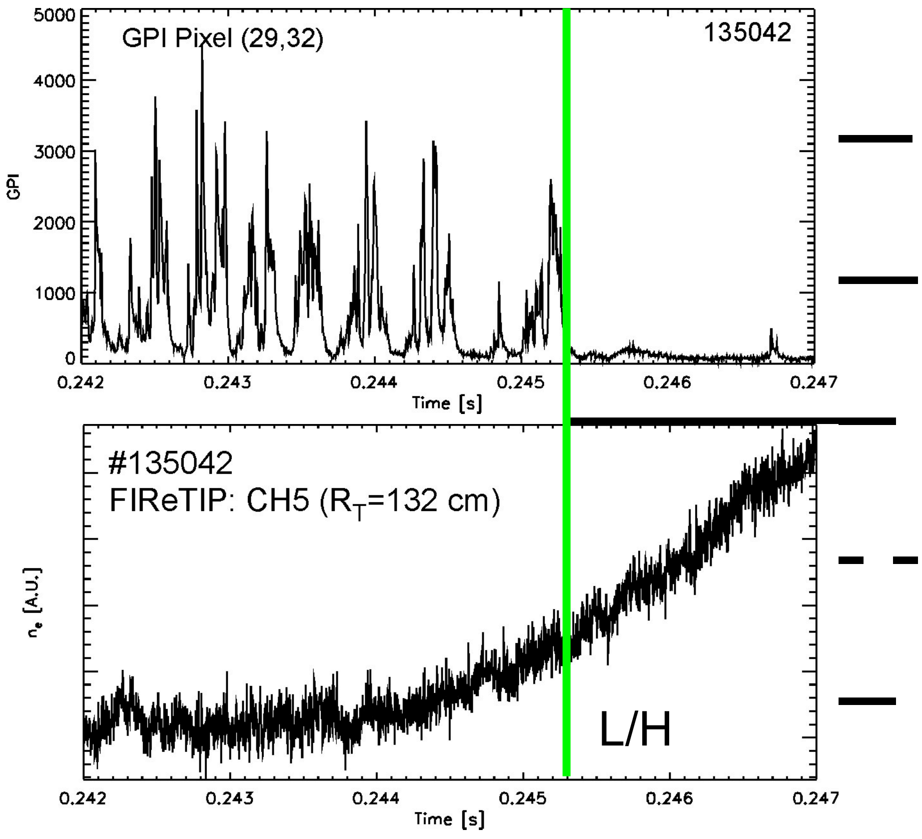
- Within <1ms before L-H transition:
  - Indications of an increase in the total level of coupling
  - Turbulence character changes

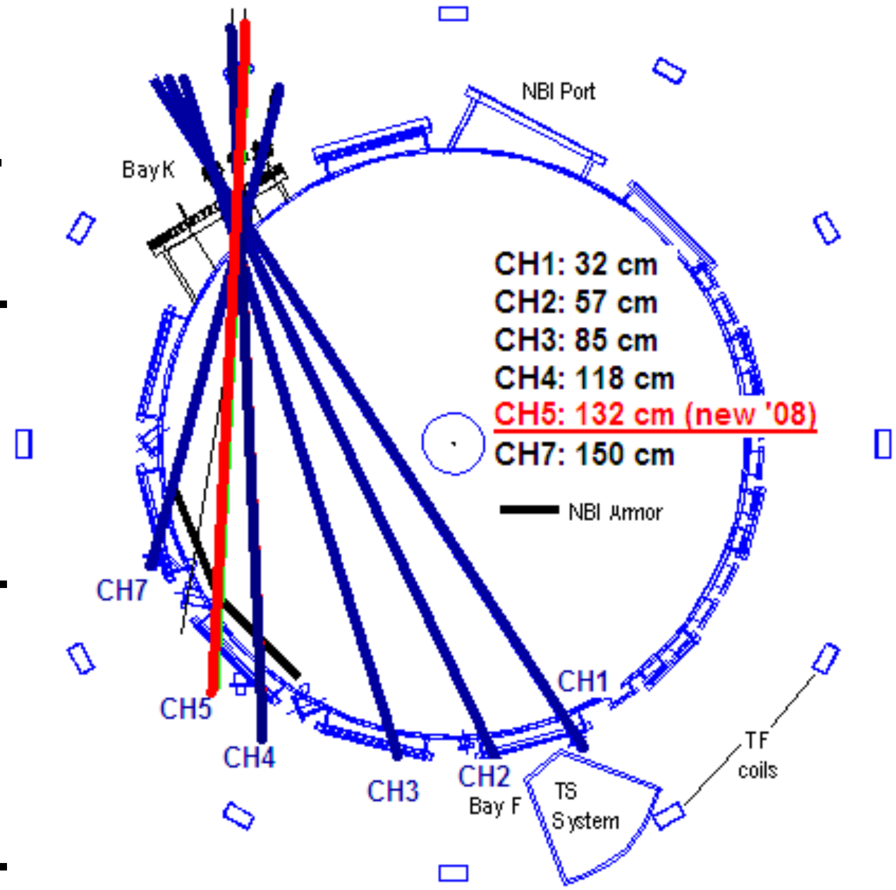
    FROM **coupling between small and large scales**

    TO **mostly coupling at intermediate-large scales**

- After L-H transition
  - Drop in the total level of coupling observed
  - Residual coupling between small and large scales

Comparison of GPI with FIReTIP n_e Measurement

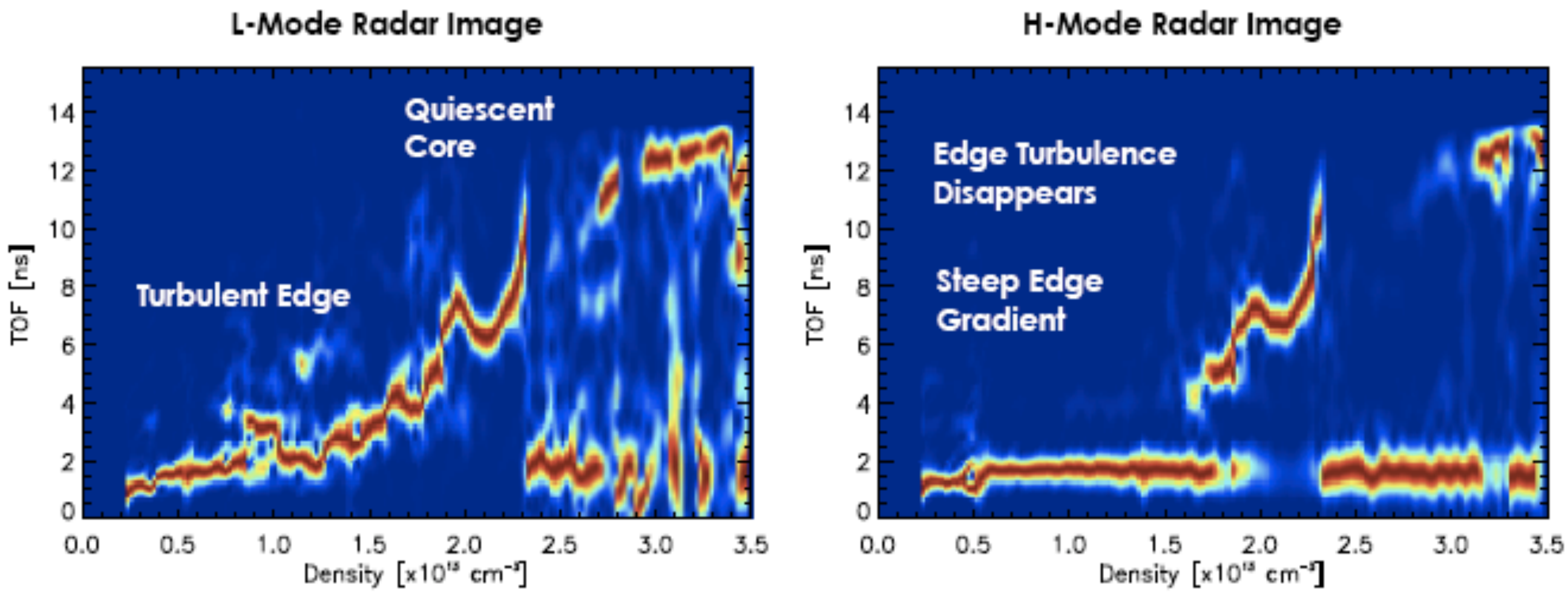




- FIReTIP density fluctuation shows weak correlation
- FIReTIP density rising earlier than L/H transition

K.C. Lee
UC Davis

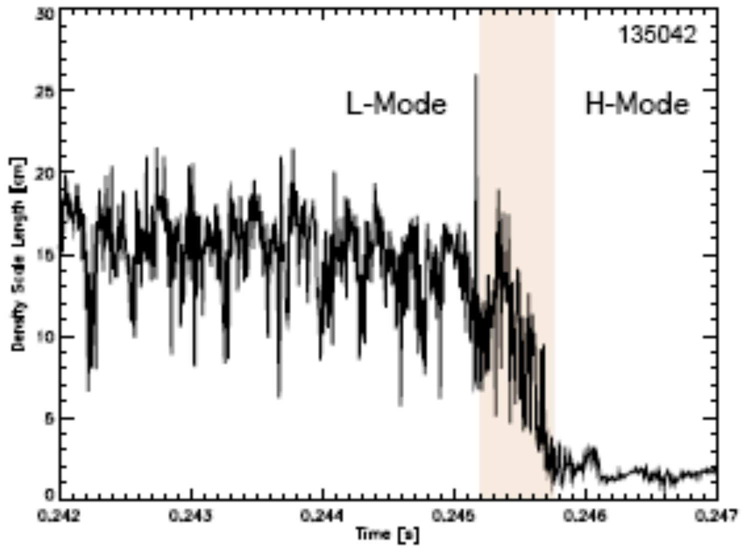
Density Turbulence and Profile Information from FMCW Reflectometry

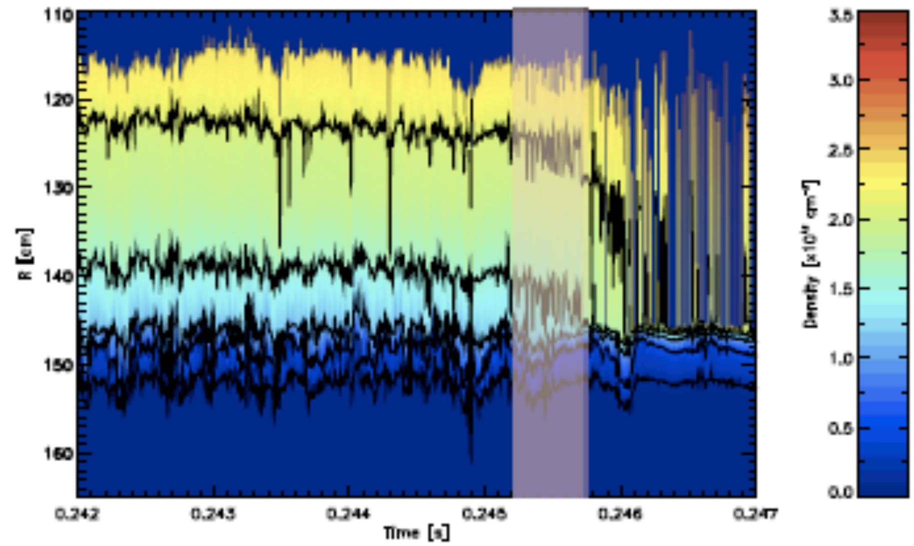


- **FMCW reflectometry radar image similar to "ionogram".**
  - Radial snapshot of electron density profile and turbulence with 7 μs time resolution.
  - Images show low-k (reflection near cutoff) and high-k (reflection away from cutoff) turbulence.
  - See poster by S. Kubota for details of the analysis techniques.

(S. Kubota)
PP8.00064

Electron Density Profile Evolution





- **FMCW reflectometry (Δt=7 μs) tracks fast evolution of the electron density profile near the L-H transition.**
  - Edge gradient begins to increase ~1 ms for transition.
  - Density at the edge (below ~1.5x10^{13} cm^{-3}) dithers between L-mode and H-mode gradients (t=0.2452 and 0.2458 s).
  - Rapid oscillations in the density scale length in a few tens of μs.

(S. Kubota)

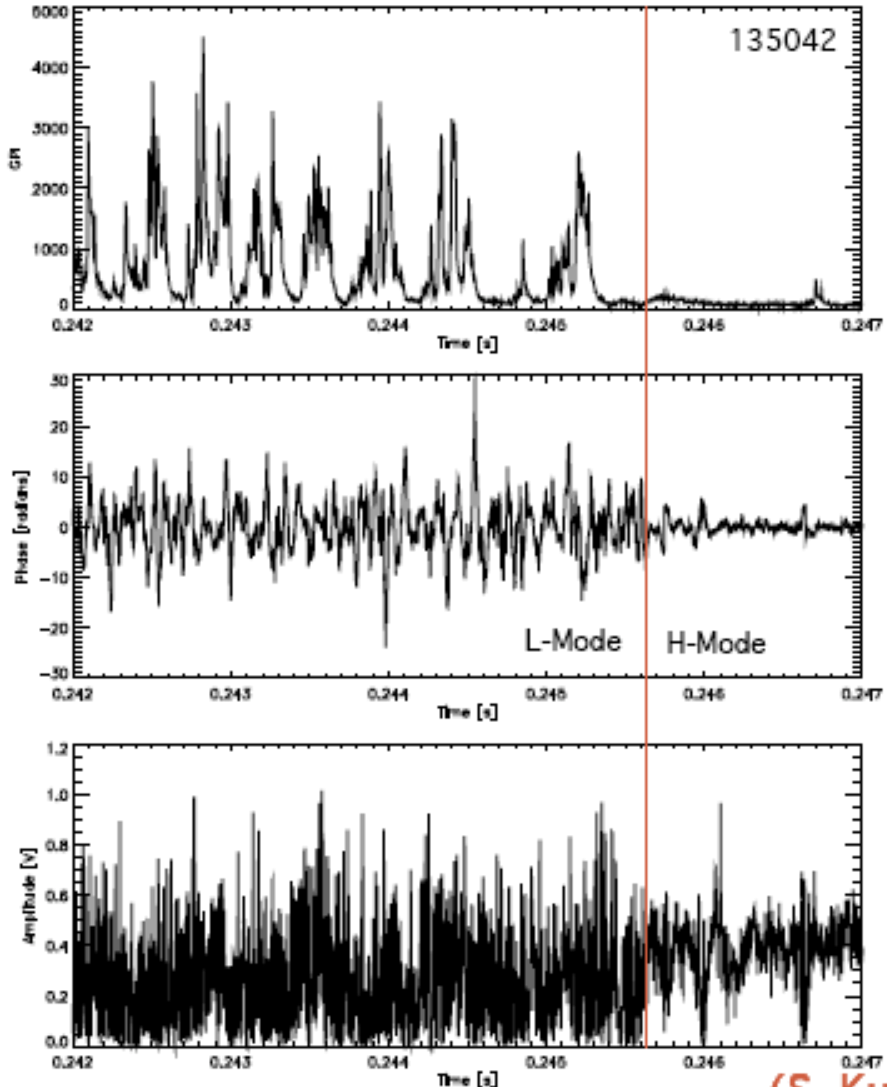
Comparison of Reflectometer Phase With GPI

GPI Pixel (29,32)

30 GHz Reflectometer Phase

$\propto \delta n/n$

30 GHz Reflectometer Amplitude



(S. Kubota)

Summary of NSTX L-H Transition

- L-H transition measured with GPI at ~300,000 frames/sec
- SOL turbulence drops over ~100 μsec at L-H transition
- Fast dithers, i.e. H-mode-like quiet times, occur before the main L-H transition with a frequency of ~3 kHz
- Poloidal velocity changes sign to EDD direction during these fast dithers
- Some changes in mode coupling ≤1 msec before transition
- Reduction in SOL turbulence seen with GPI seems to precede drop of turbulence seen inside SOL with reflectometer