NSTX

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Quiet periods, zonal flows, and blob formation in the edge turbulence of NSTX*

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* Work supported by US DoE contract DE-AC02-09CH11466

52nd APS DPP Meeting
Chicago, Illinois, November 9, 2010

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Quiet Periods and Zonal Flows

Original motivations:

- Identify the 'trigger' mechanism for the L-H transition
- Understand the mechanism for edge 'blob' formation

led to experiments with surprising results:

- **H-mode-like 'quiet periods' (i.e. no blobs) during L-mode**
- **poloidal 'zonal' flow correlated with these quiet periods**

Outline of Talk

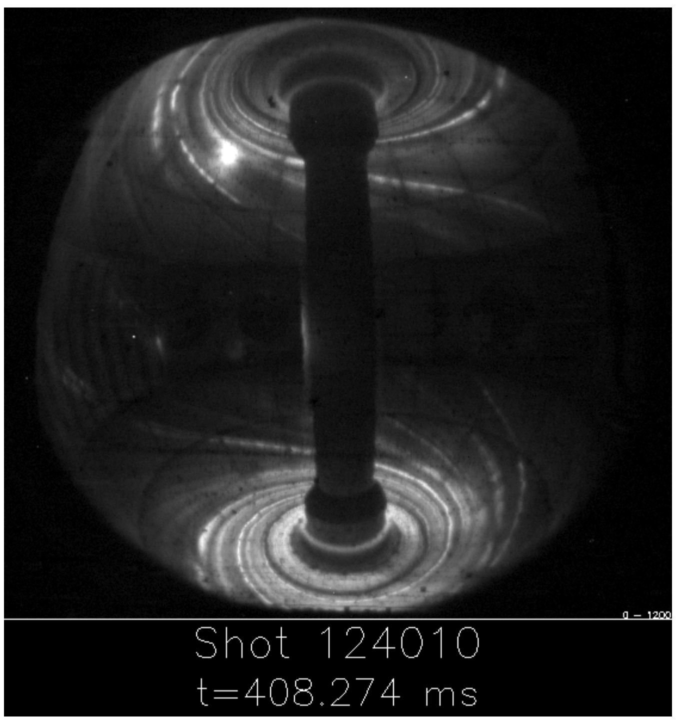
- Edge blobs and the gas puff imaging (GPI) diagnostic
- Quiet periods preceding the L-H transition
- GPI measurement of edge ‘zonal flows’
- Preliminary comparisons with theory
- Zonal flows in other discharges
- Summary and open questions

Edge Turbulence "Filaments" in NSTX

- Fluctuating "filaments" can be seen in the edge where ever there is visible light emission, e.g. due to recycling

- These are well-correlated for many meters along B from the outer midplane to divertor plate (Maqueda et al, NF 2010)

Li I filter

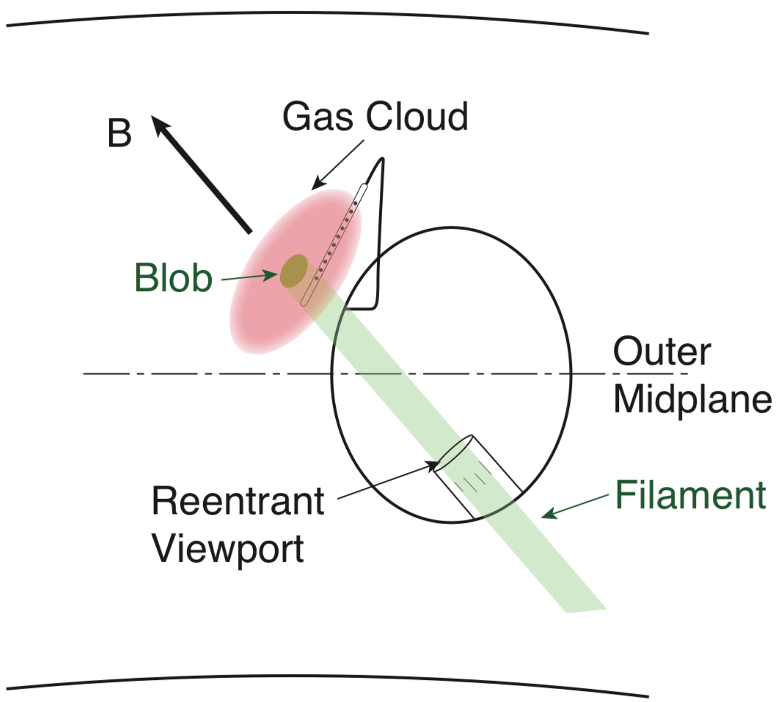


similar filaments seen in MAST and well correlated with density fluctuations in nearby Langmuir probe (Ben Ayed, PPCF 2009)

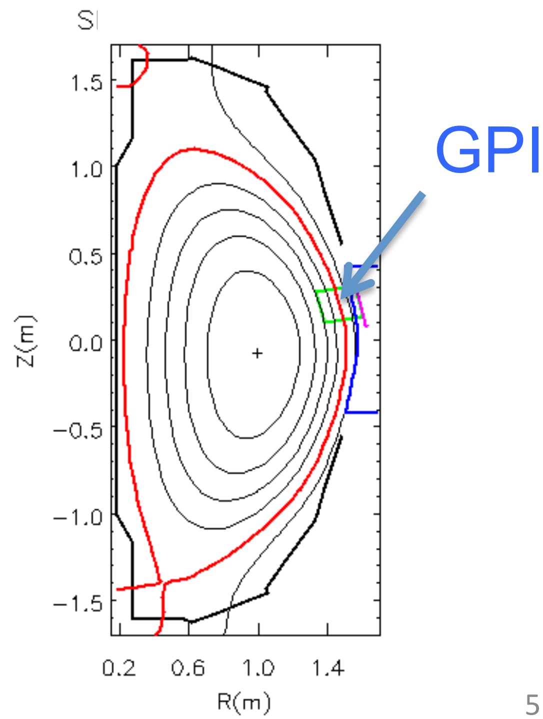
Gas Puff Imaging (GPI) Diagnostic

- Optics view along B toward D_α emission from D_2 gas puff
- Oriented to view 2-D radial vs. poloidal plane at gas cloud

GPI at NSTX outer wall

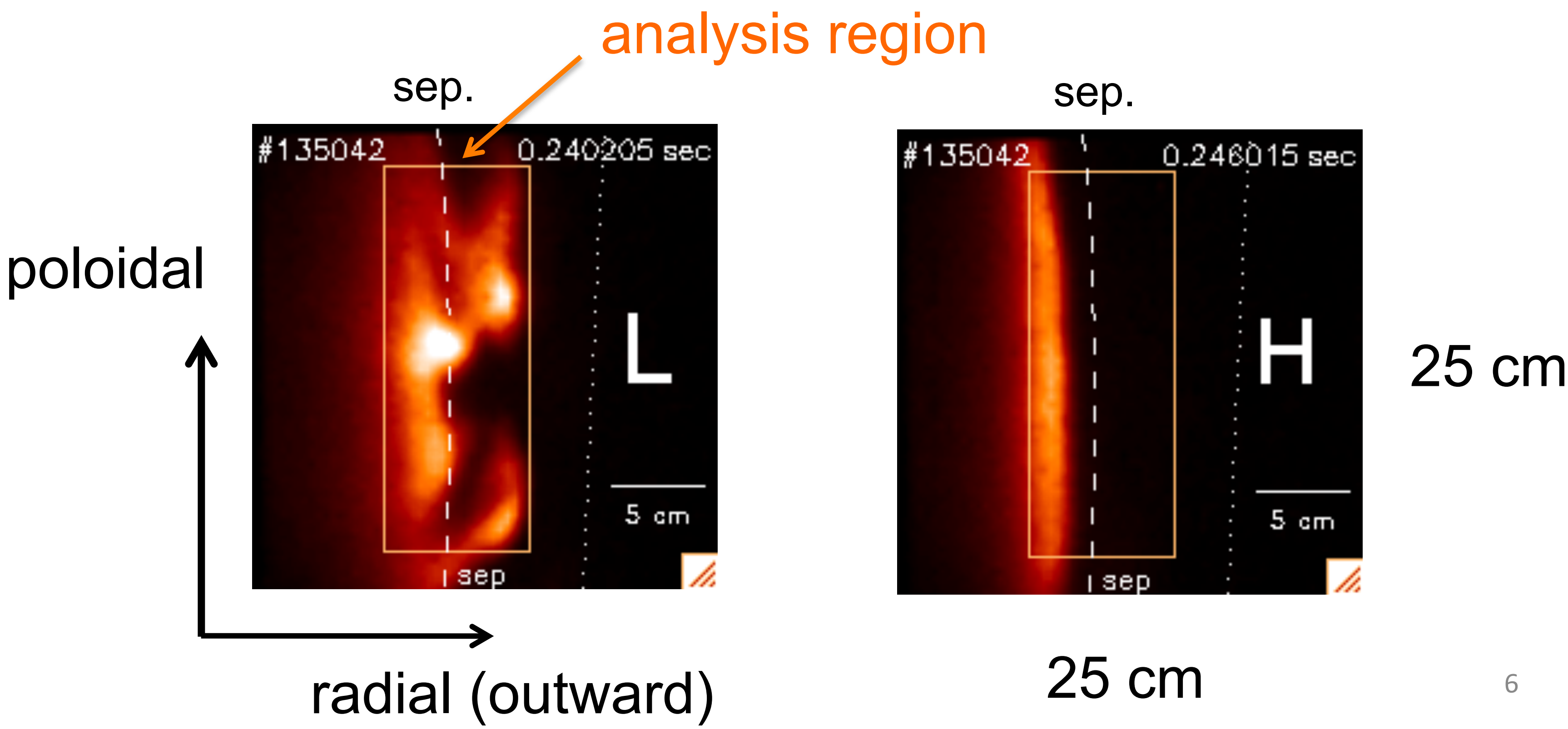


GPI location



Typical Images of D_α from GPI Diagnostic

- L-mode has turbulent ~3-4 cm sized blobs near separatrix
- H-mode has quiescent band of emission inside separatrix
- GPI profile in H-mode agrees with DEGAS-2 (Stotler JNM 2007)



What Are We Seeing in GPI ?

- Seeing local emission of $D_\alpha \sim n_o\, f(n_e,T_e)$ within window where D_α emitted ($\rho \sim \pm$ 4 cm around separarix @ $T_e \sim$ 10 -100 eV)
- Can measure 2-D ***turbulence structure and motion*** even if response of D_α is nonlinear (like contrast knob on a TV)
- Can ***not directly measure fluid (ion) flow*** or ExB flow, but measures turbulence flow velocity, as done previously*

* McKee et al, PoP '03 using BES on DIII-D
Conway et al, PPCF '05 using Doppler reflectometry on AUG

Movies of Edge Turbulence as Seen by GPI

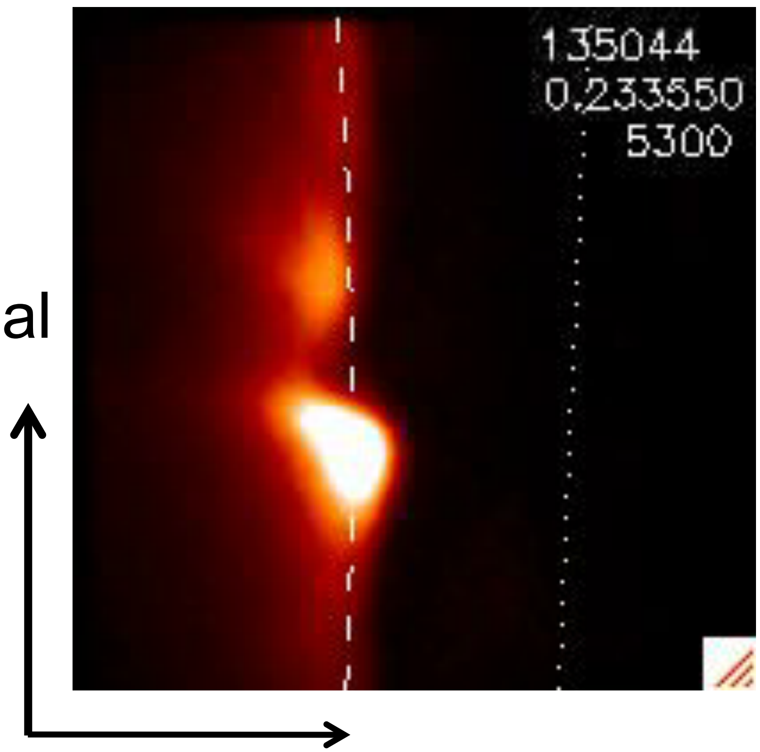
- Taken up to 400,000 frames/sec for ~ 50 msec per shot
- This movie 285,000 frames/sec for ~ 1.4 msec in L-mode

electron
diamagnetic
drift direction
(EDD)

(IDD)
ion diamagnetic
and ion grad-B
drift direction

sep.

poloidal

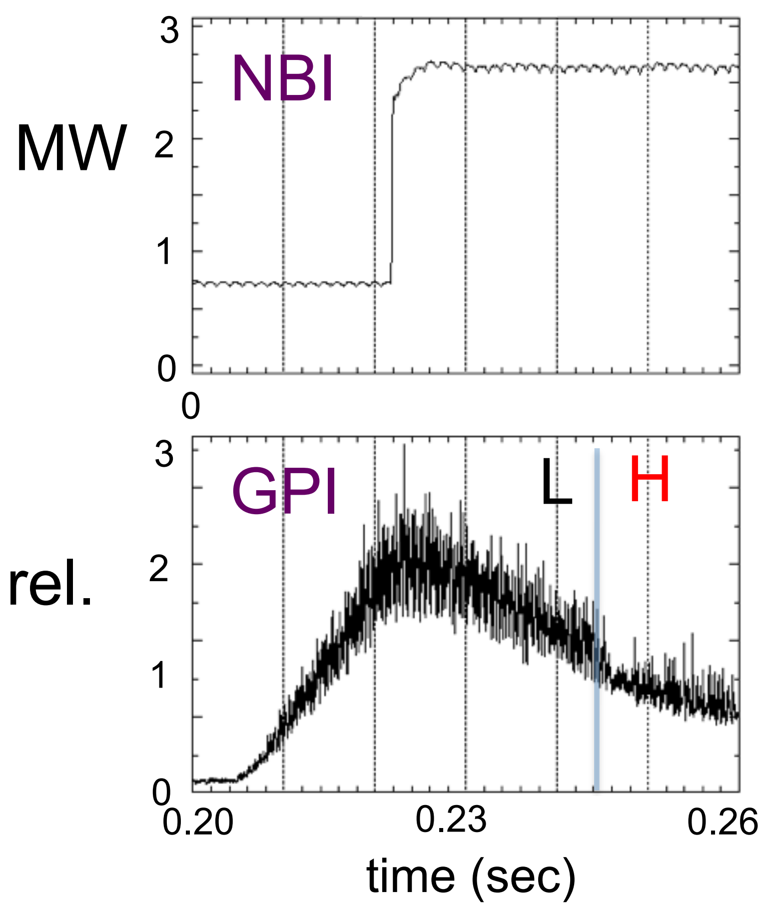


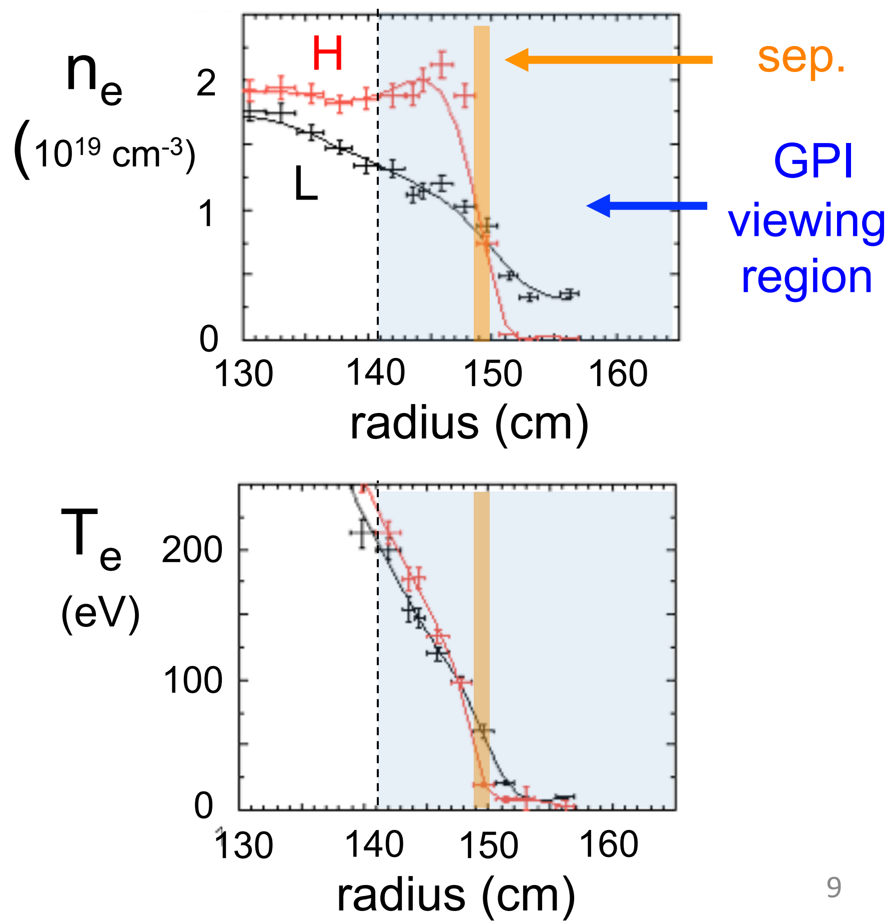
radial (outward)

playback @
35 μsec/sec

Experiment on L-H Transition in NSTX

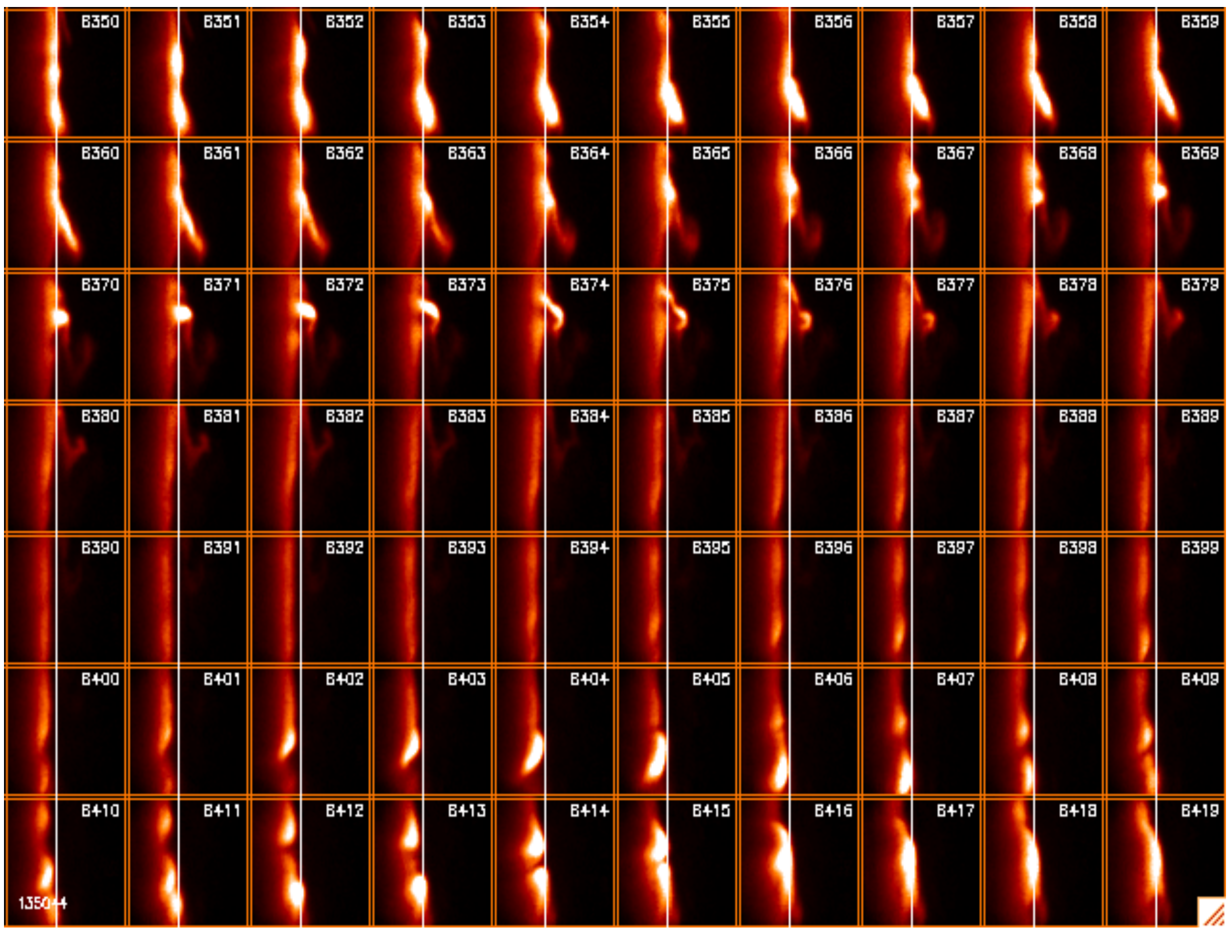
- Use standard discharge (B=4.5 kG, I=0.9 MA, LSN) and increase NBI power to look at L-H transition





“Quiet Periods” Appear in L-mode Plasma

- Transient ‘quiet periods’ in L-mode have little or no blob formation and transport into SOL (~ like H-mode)



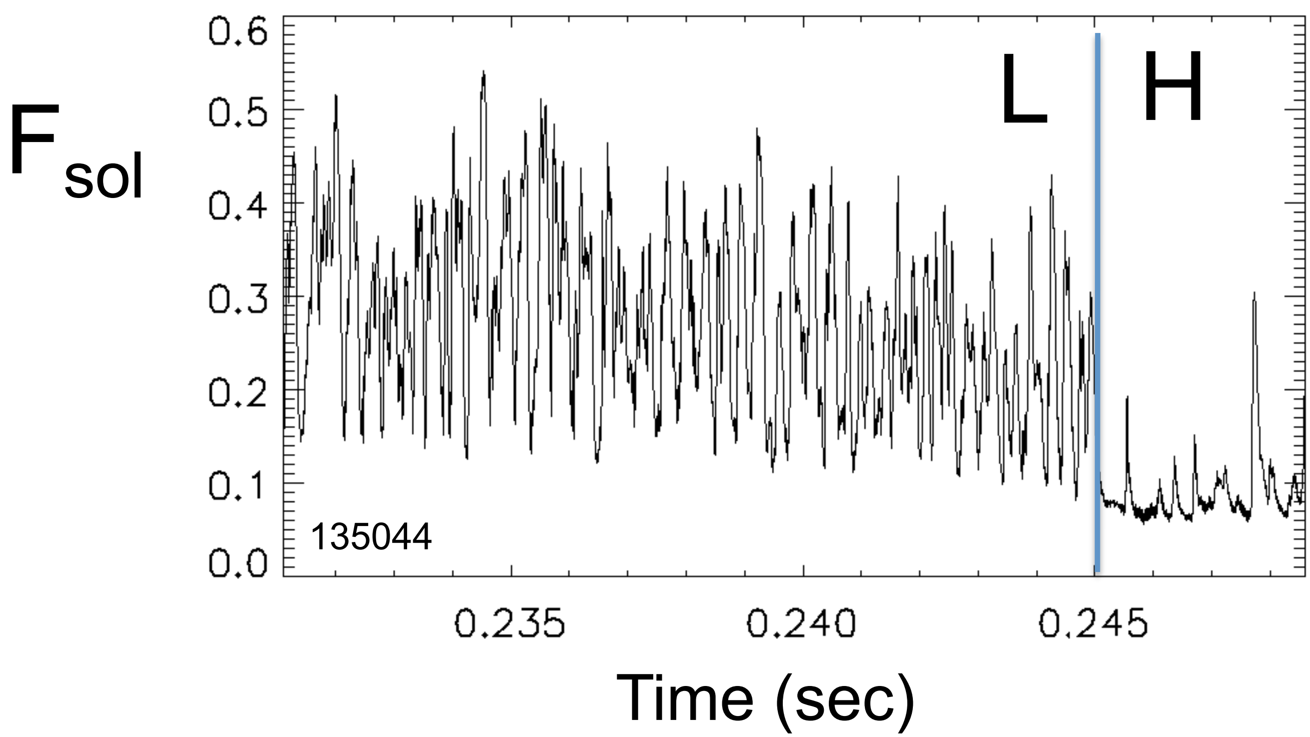
3.5 μsec/frame

7 msec before L-H transition

Quiet
70 μsec

Quantitative Measure of Quiet Periods with F_{sol}

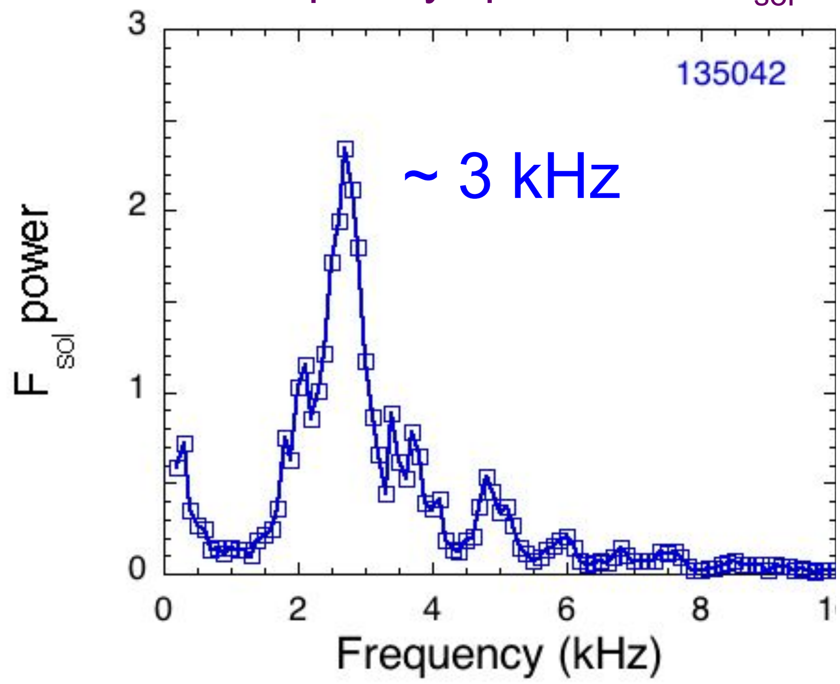
- Fraction of GPI light outside separatrix = F_{sol} (0 to 1)
- Low F_{sol} = quiet period = no blob formation (≤ 0.2 or so)
- F_{sol} is a ‘proxy’ for fast edge profile changes



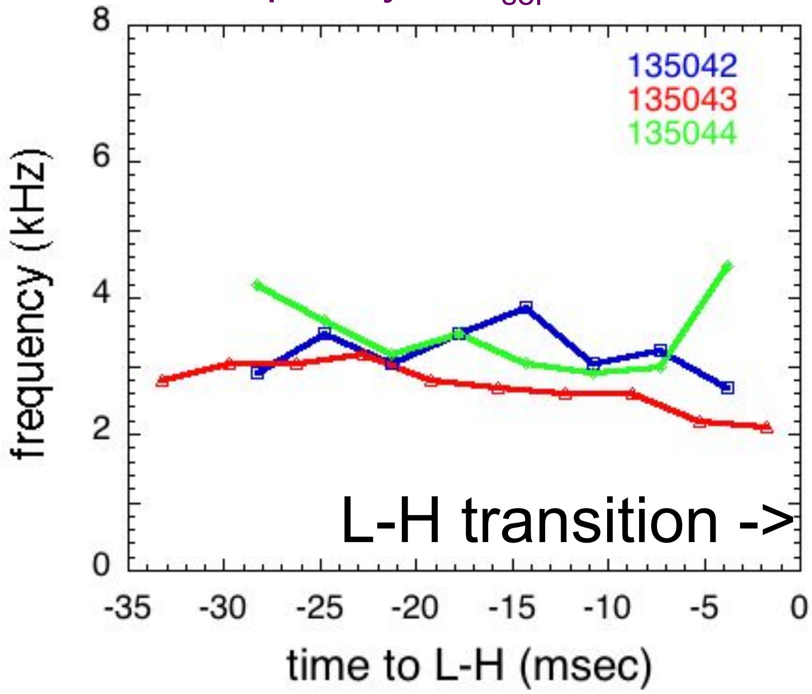
Frequency and Duration of Quiet Periods

- Quiet periods occur at a frequency approximately f ~ 3 kHz
- No systematic change in quiet periods just before transition
- Quiet periods also in L-mode plasmas without L-H transition

frequency spectrum of F_{sol}



frequency of F_{sol} vs. time

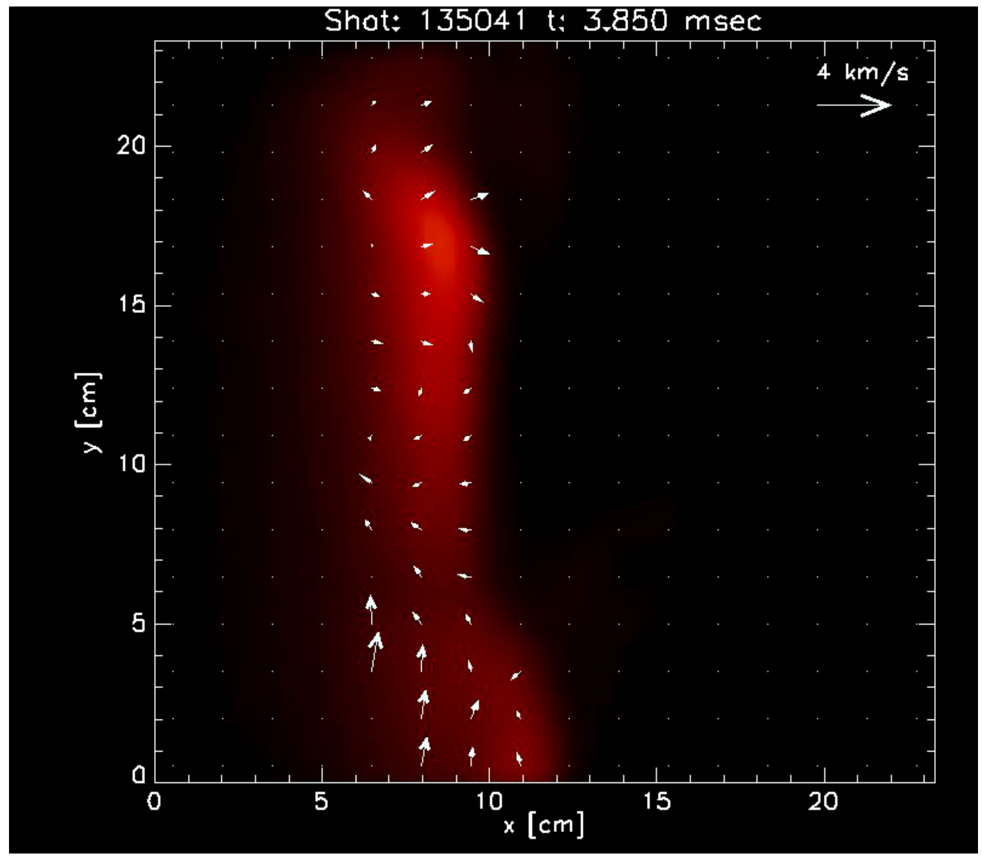


GPI Measurement of Turbulence Flow Velocity

- Calculate turbulence flow from two independent methods
  1) 2-D cross-correlation between frames over ± 40 μsec, which can find velocity fields for f ≤ 10 kHz

  2) HOP-V code (Munsat RSI ‘06)

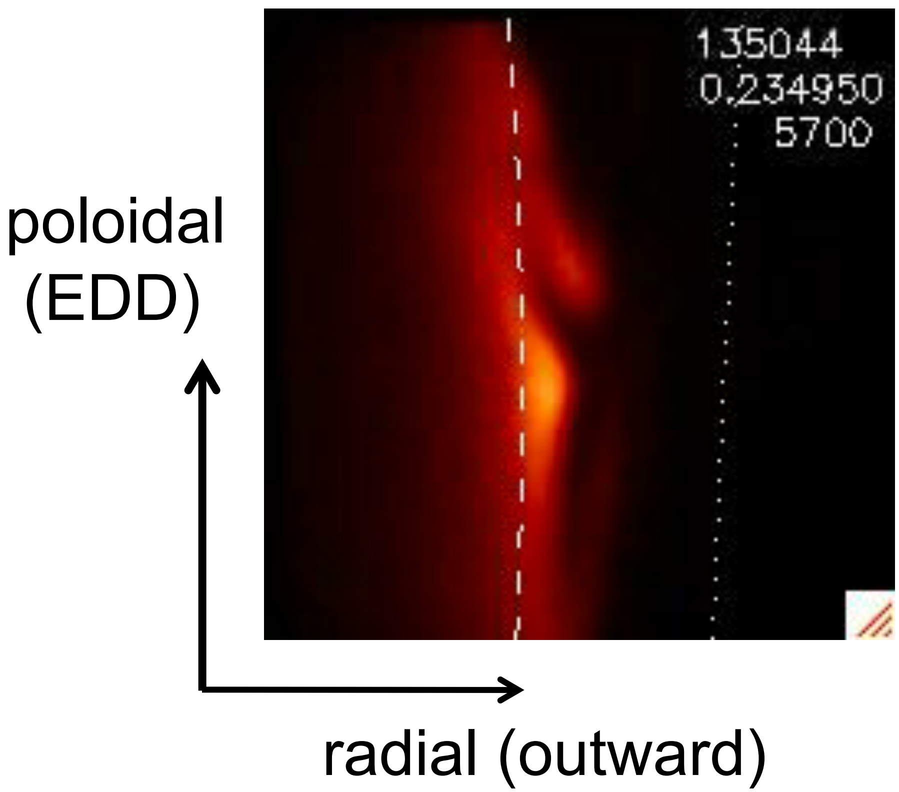
     2-D optical flow + pattern matching can find velocity fields for f ≤ 100kHz



these two methods agree well for f ≤ 10 kHz

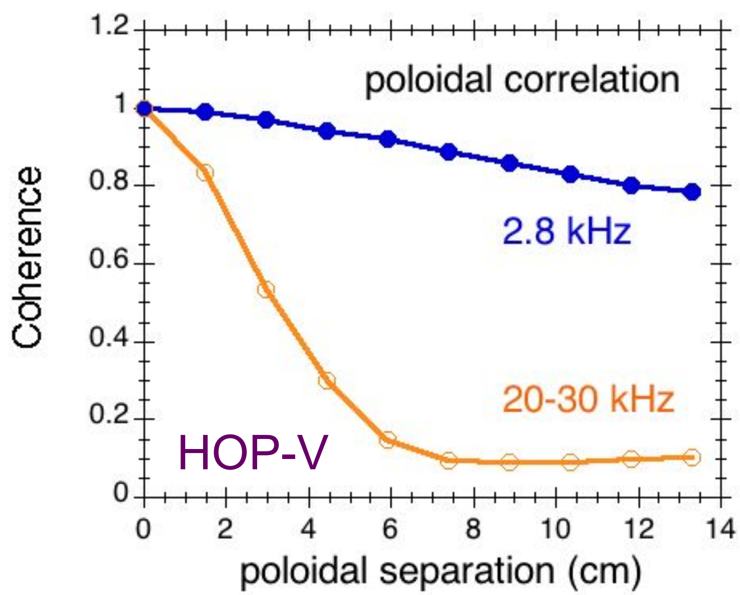
Poloidal Flow Reverses During Quiet Periods

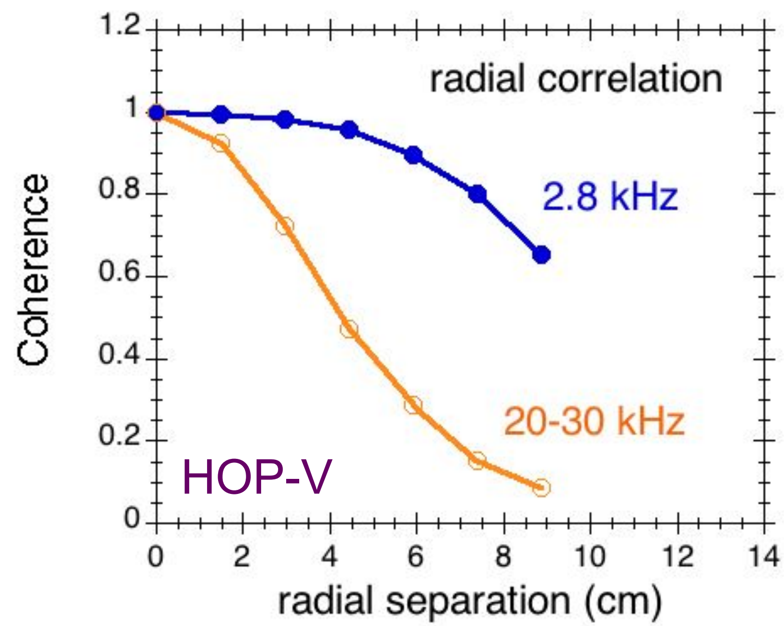
- Poloidal flow near separatrix in EDD near quiet periods
- Poloidal flow near separatrix in IDD in blobby periods
- Poloidal flow of blobs outside separatrix usually in IDD



2-D Structure of Velocity Fields

- ~3 kHz frequency << turbulence (typically ~ 10-100 kHz)
- ~3 kHz poloidal correlation >> turbulence (λ_{pol} > 100 cm)
- ~3 kHz radial correlation ~ 3 x turbulence (~ 10 cm)

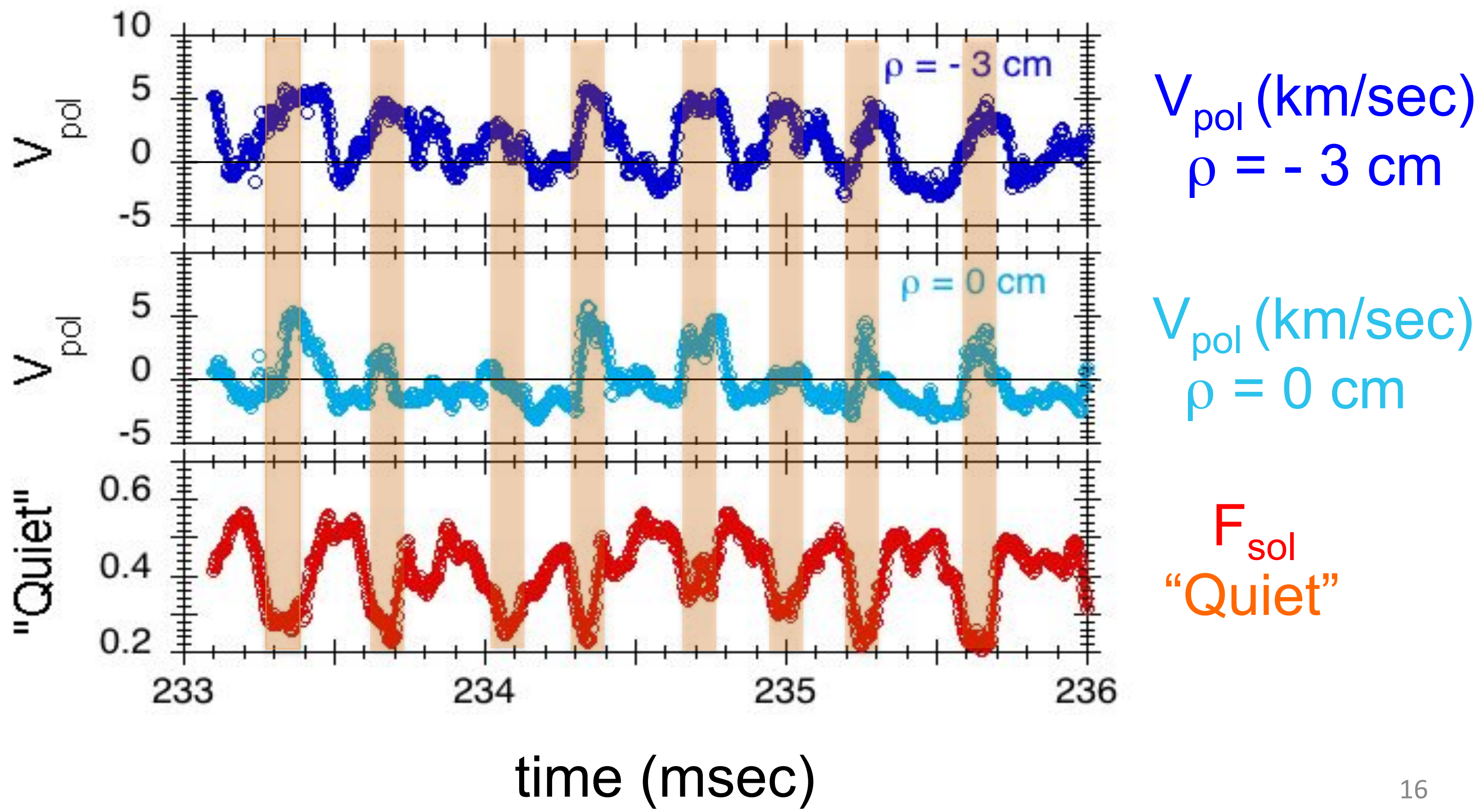




3 kHz structure looks like "zonal flow" (Fujisawa PPCF '09)

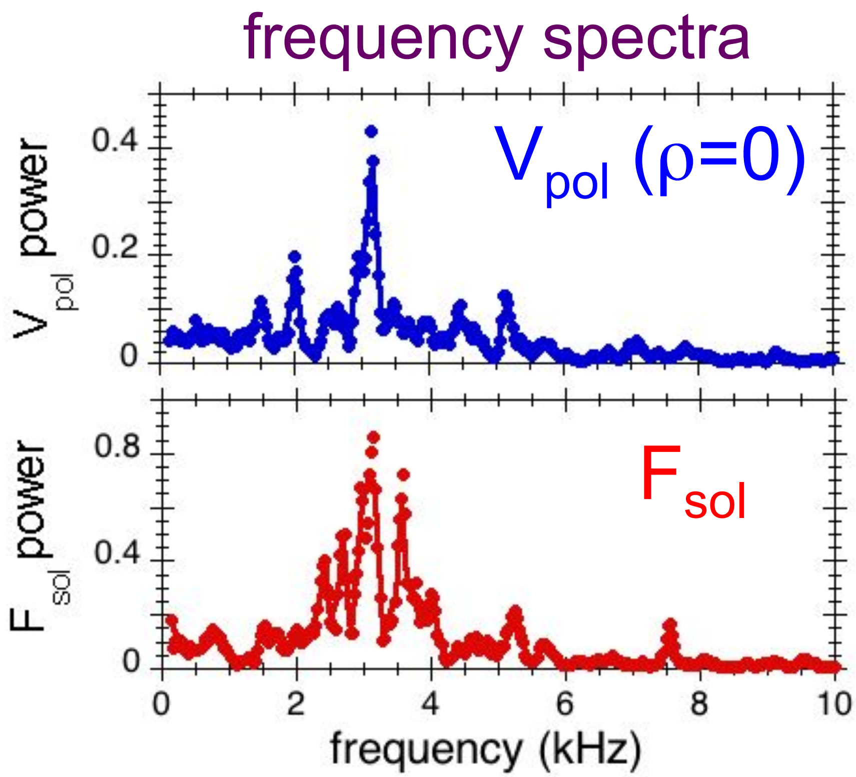
Quiet Periods Correlate with Poloidal Flow

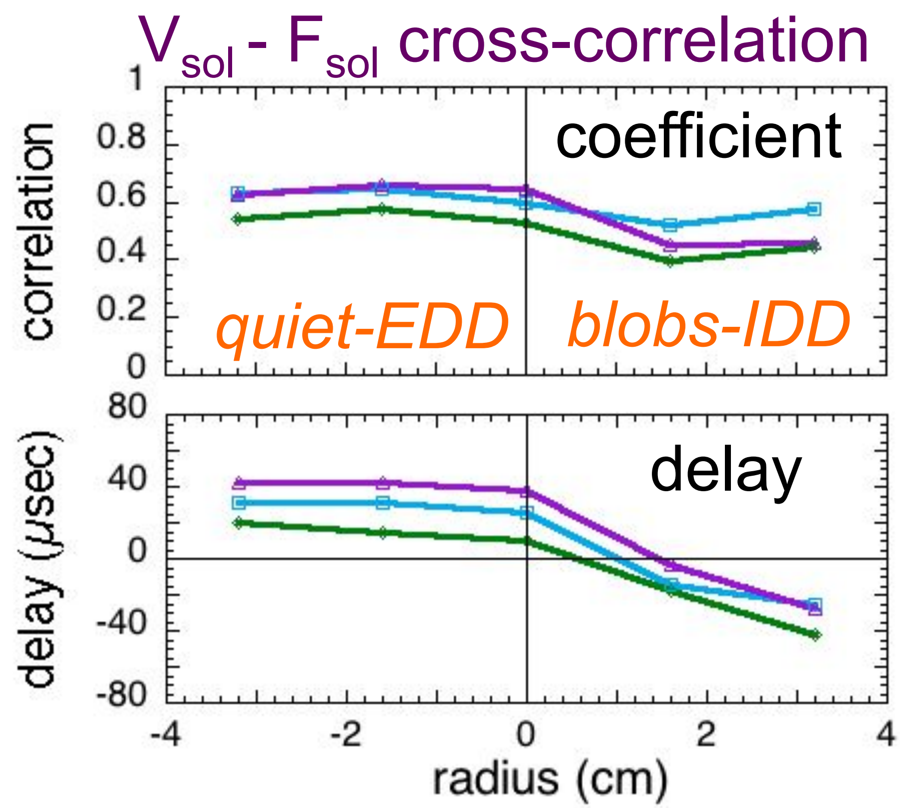
- ***Average the local V_{pol}*** over 20 cm poloidally at each radius
- Quiet periods when this average V_{pol} is in the EDD direction



Correlation of Quiet Periods and Zonal Flow

- Average V_{pol} and F_{sol} spectra both peak near 3 kHz
- Cross-correlation of V_{pol} and F_{sol} ~ 50% over $\rho = \pm 3$ cm
- Quiet inside separatrix preceds flow in EDD direction

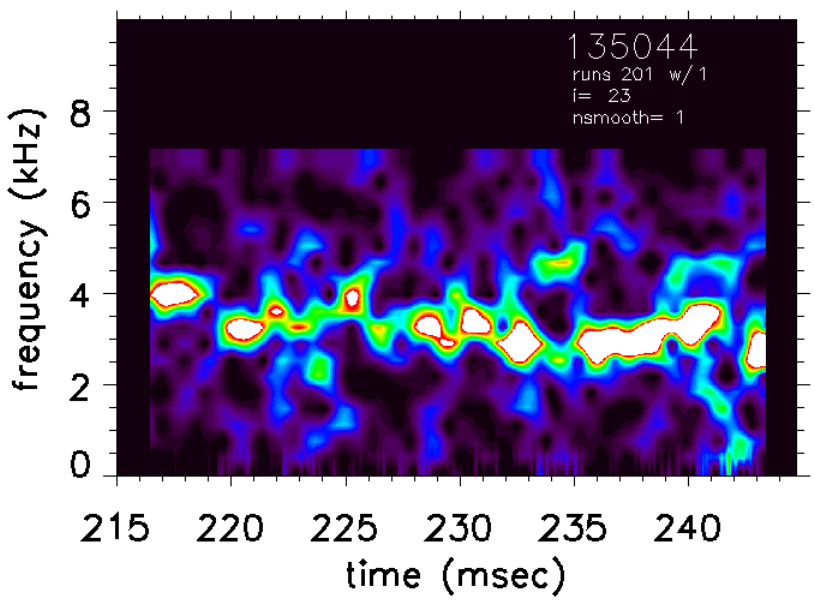




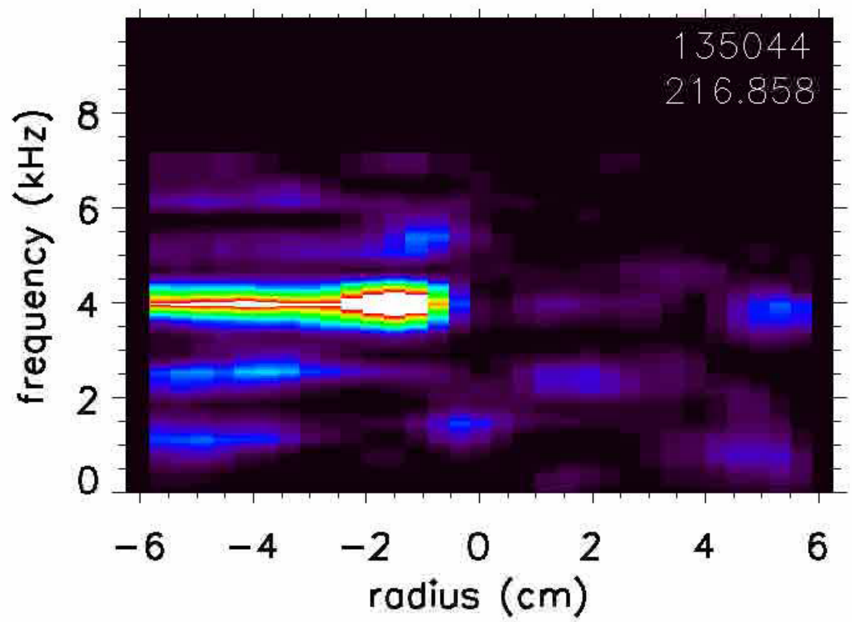
Time and Radial Dependence of Zonal Flow

- Zonal flow spectrum intermittent in frequency and amplitude
- Zonal flow amplitude largest $\rho \sim 0$ to -5 cm inside separatrix

V_{pol} spectrum at $\rho = -2$ cm



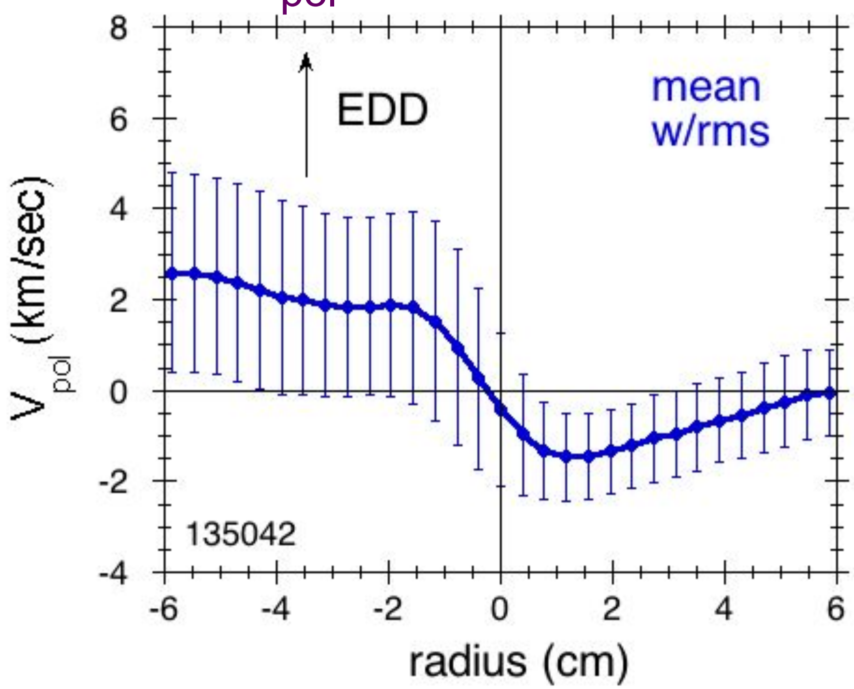
V_{pol} spectrum vs. ρ vs. time



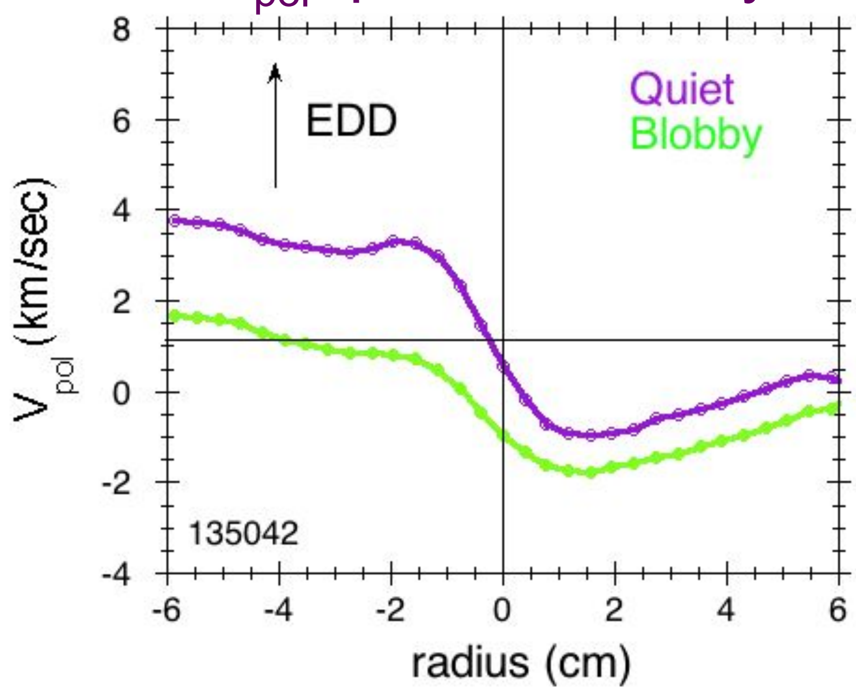
Magnitude of Mean and Zonal Flow vs. Radius

- Fluctuating zonal turbulence flow V_{pol}(rms) ~ V_{pol} (mean)
- Magnitude of fluctuating zonal flow ± 2 km/sec (~ 5% c_s)
- Shape of mean flow similar in quiet and blobby periods

V_{pol} mean and rms

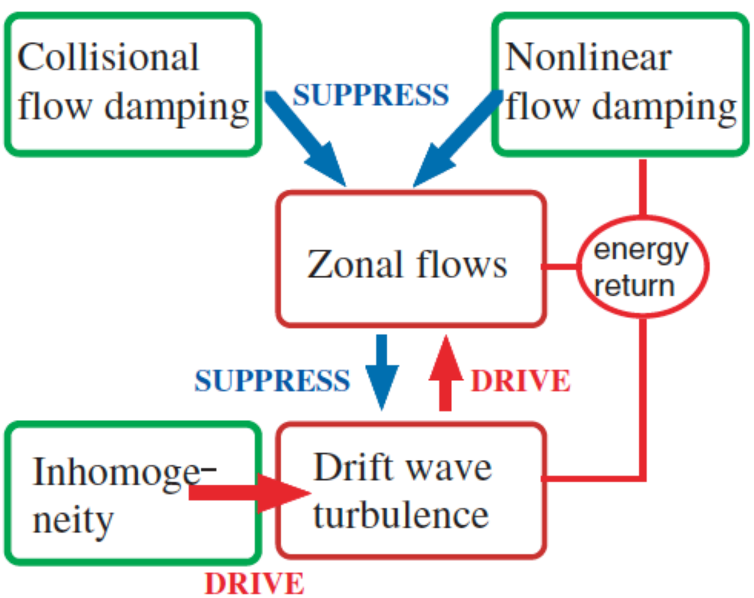


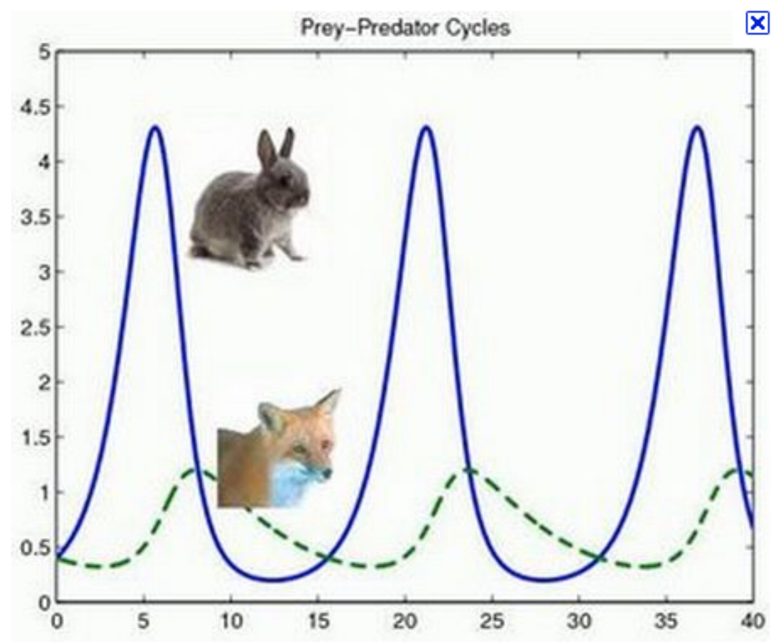
V_{pol} quiet vs. blobby



Connections to Theory (Preliminary)

- Models for ‘drift-wave-zonal-flow’ interaction proposed
- “Predator-prey” dynamics used to describe interaction





Diamond et al, PPCF ’05
Tynan et al, PPCF ‘09

Stroth, APS DPP ‘09
Fujisawa PPCF ‘09

Geodesic Acoustic Mode (GAM) in NSTX

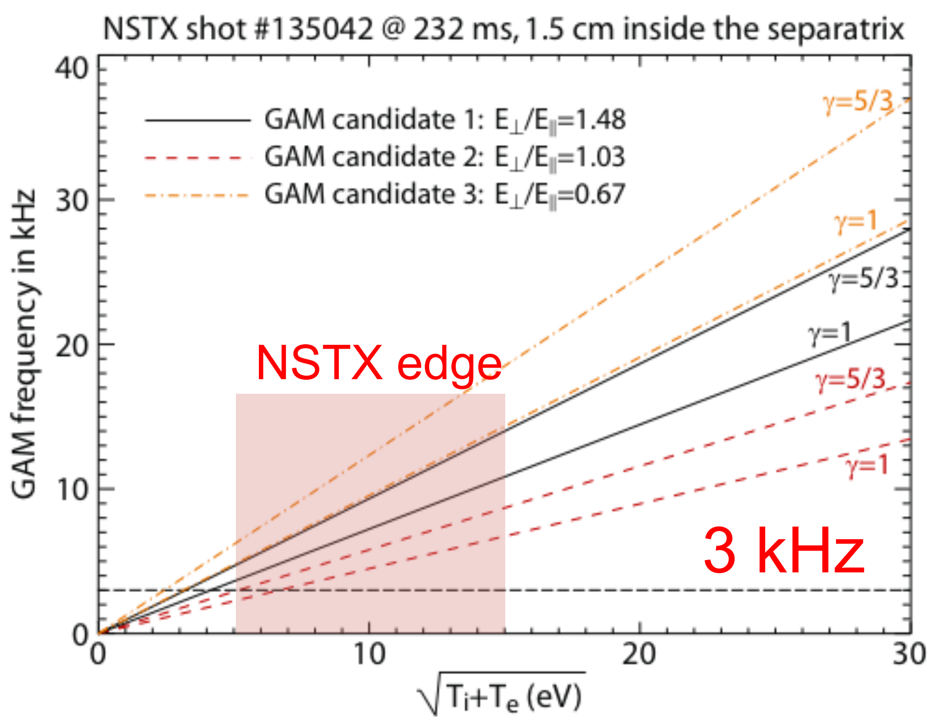
R. Hager, K. Hallatschek, IPP Garching

- GAM expected roughly at $f = G\,(1/\pi R)\,[\gamma(T_i+T_e)/m_i]^{1/2}$
- For NSTX case G (geometry factor) = 0.31, 0.49, 0.65

- linear simulations show GAMs at f ~ 4.6-12.3 kHz for $T_e \sim T_i \sim 50$ eV

- nonlinear simulations show low frequency GAM at f ~ 6.3 kHz

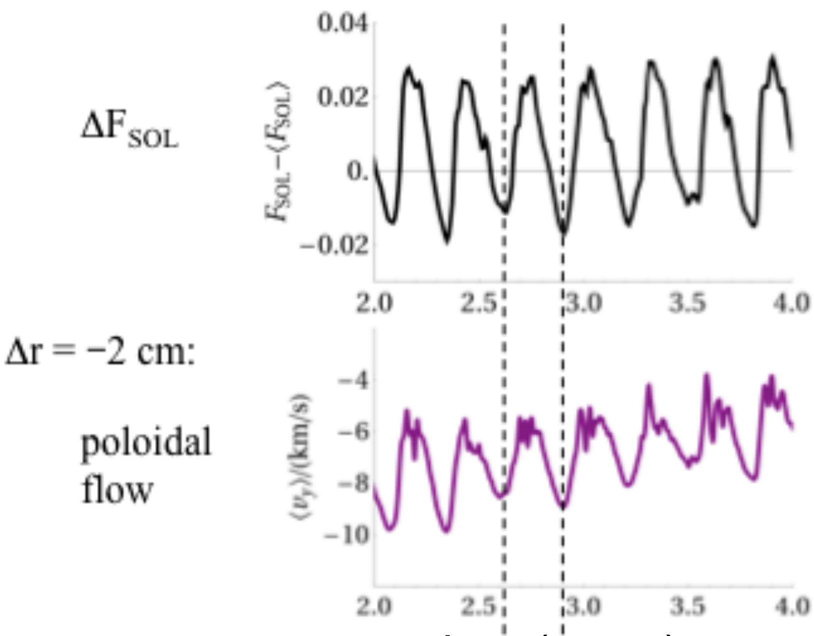
➡ ***close to ~ 3 kHz***

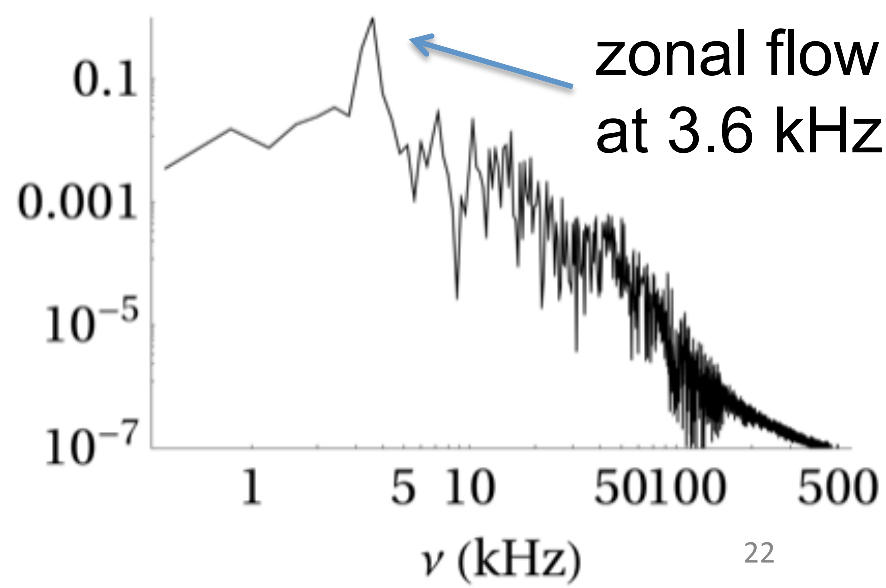


2-D Simulation of Edge Zonal Flow in NSTX

D.A. Russell, J.R. Myra, D. A. D'Ippolito - Lodestar

- SOLT code shows edge 'bursts' with f ~ 3 4 kHz along with edge zonal flows which are *not* GAMs (Russell, PoP 2009)
- Zonal flow frequency increases with edge profile relaxation rate (~ c_s/R) and assumed zonal flow viscosity





Zonal Flows in Other Discharges

- All previous data in L-mode ≤ 30 msec before L-H transition for one type of plasma (B=4.5 kG, I=0.9 MA, ~2 MW NBI)

  see: Zweben, Maqueda et al, PoP 2010
  Sechrest, Munsat et al, submitted to PoP 2010

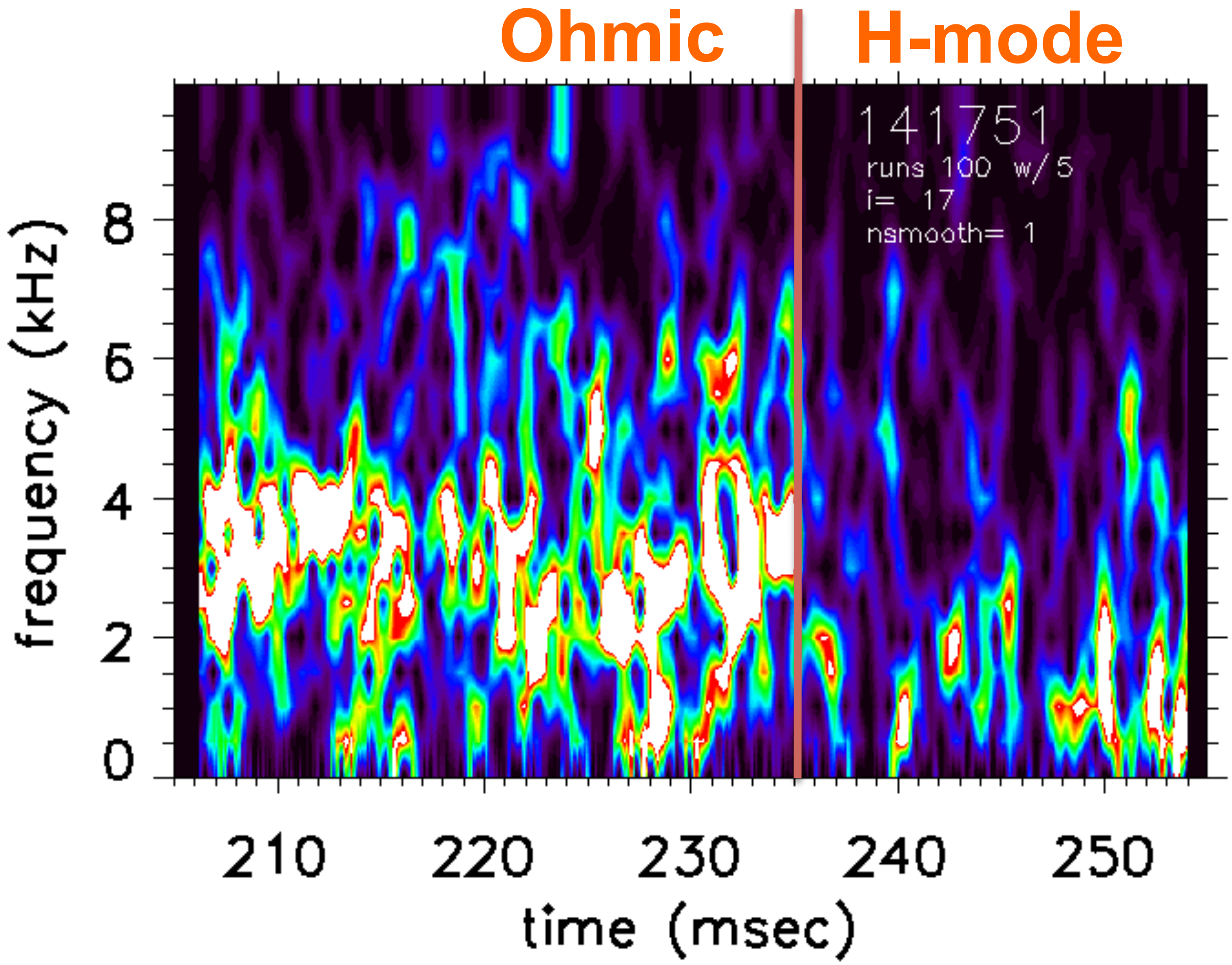
- Now have large GPI database at 400,000 frames/sec for:

  - Ohmic plasmas
  - H-mode plasmas
  - RF-heated plasmas

➡ ***similar but sometimes more complex behavior***

Zonal Flow in Ohmic and Ohmic H-mode

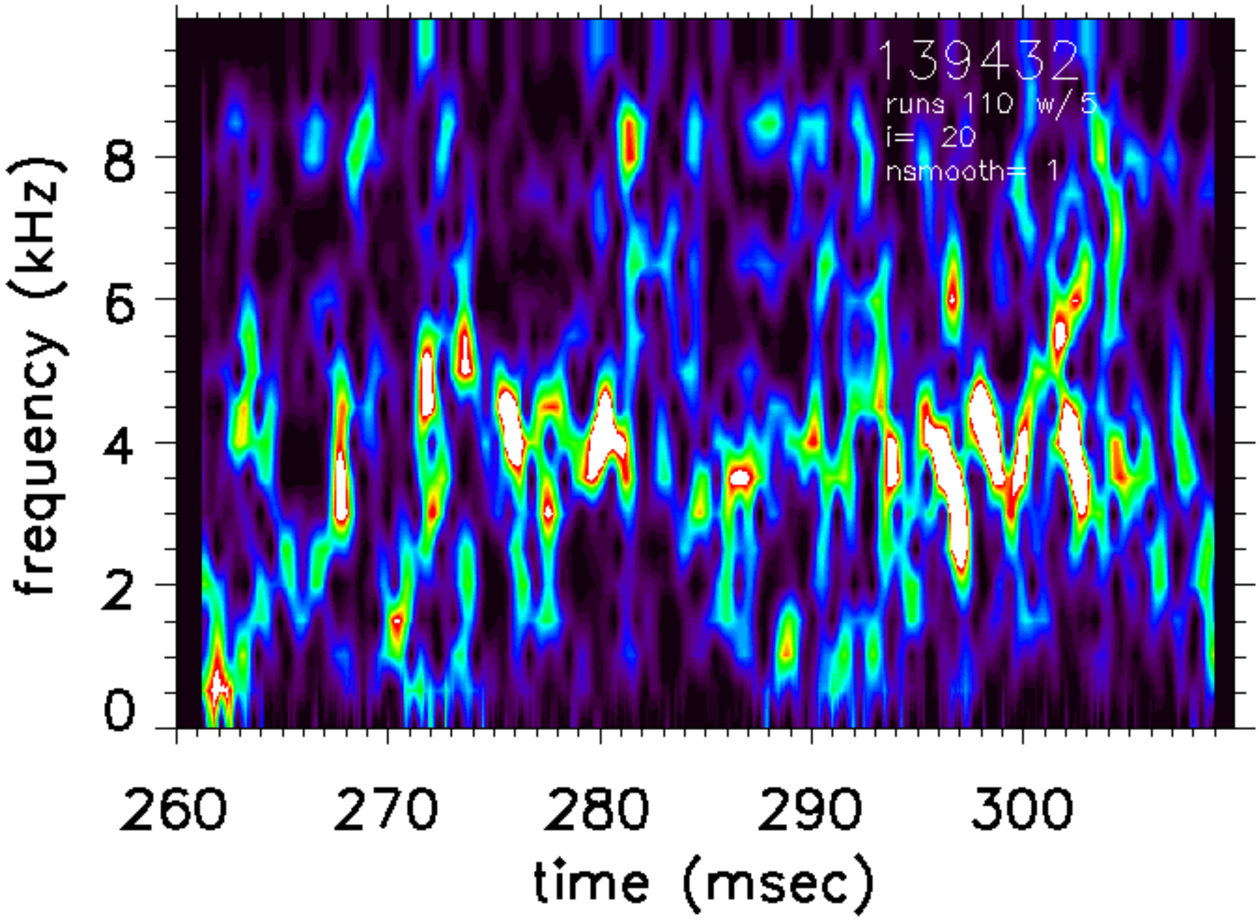
- See zonal flow at ~ 3 kHz with decrease at L-H transition (similar to previous results with NBI-driven H-mode)



V_{pol} spectrum

Zonal Flow in High Power NBI H-mode

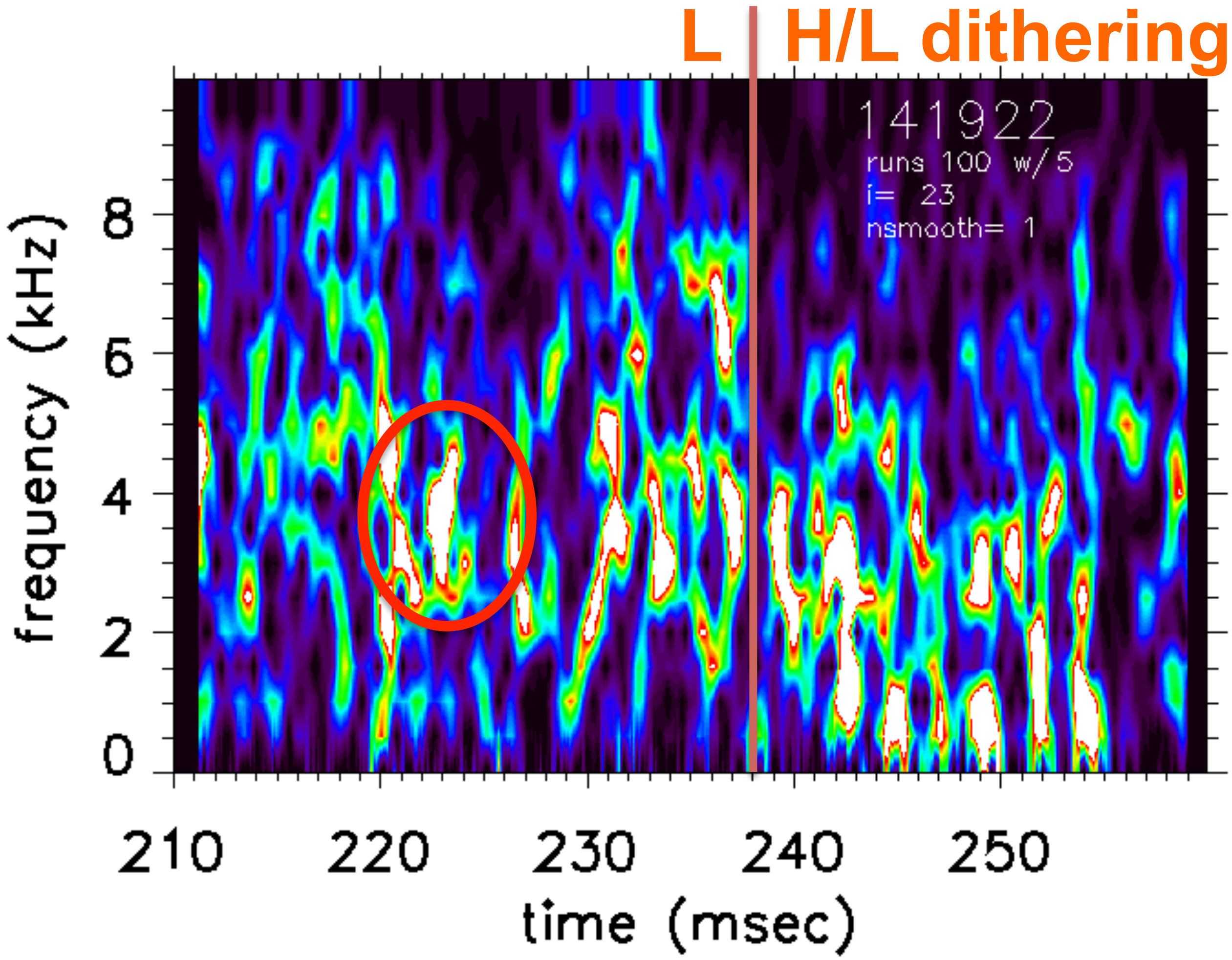
- See some zonal flow at ~ 4 kHz in high-power H-mode (6 MW)



V_{pol} spectrum

More Complex Zonal Flow Spectrum

- See broadband zonal flow with f ~ 1-5 kHz in RF L-mode with ***intermittent zonal flow bursts*** of ~ 1-2 msec

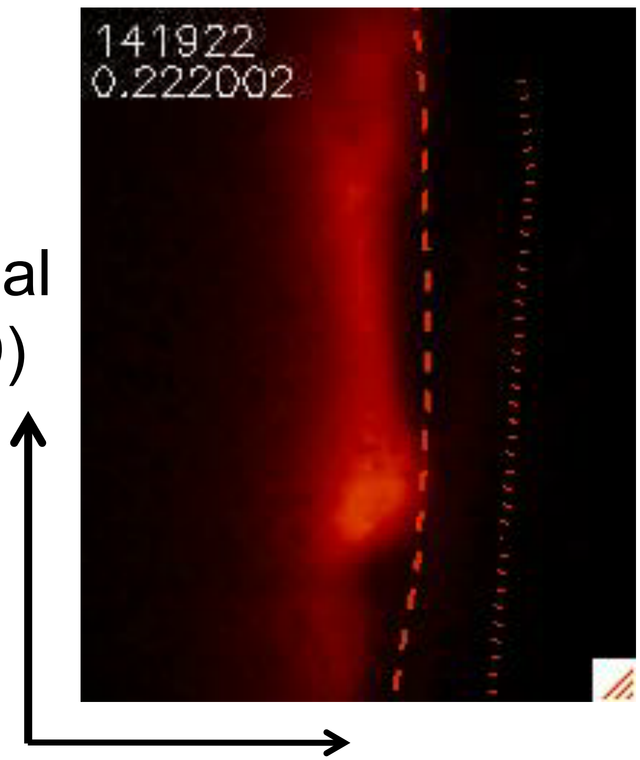


V_{pol} spectrum

Example of More Complex Zonal Flow

- Complex and intermittent (broadband) zonal flows with quiet periods which are not as clear as ~ 3 kHz case

poloidal (EDD)



radial (outward)

400,000 frames/sec

35 μsec/sec playback

burst of zonal flow detected ~ 4 kHz

Summary

- Observed H-mode-like ‘quiet periods’ in L-mode edge plasma correlated with ~ 3 kHz reversals in poloidal turbulence flow

- This behavior looks similar to ‘drift-wave-zonal-flow’ paradigm
  - poloidal flow frequency << turbulence frequency
  - poloidal correlation lengths >> turbulence correlation
  - radial correlation lengths ≥ turbulence correlation
  - modulation of amplitude of turbulence with flows

- Sometimes spectra of edge zonal flows are broadband and intermittent, for reasons which are not yet understood