On the Energy Exchange Between Flow and Turbulence across the L-H Transition

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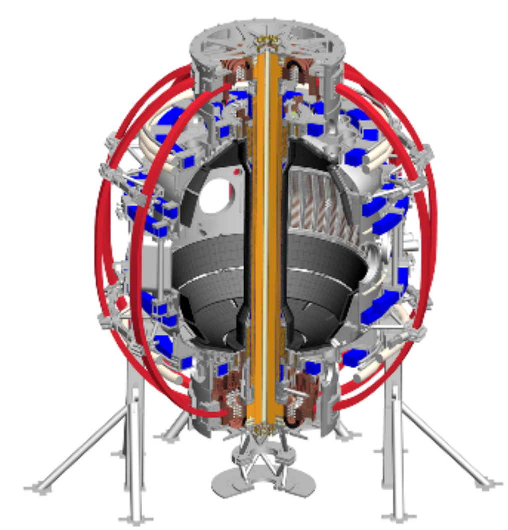


Motivation and Goal: Investigation of the link between microscopic physics and L-H transition

- Turbulence-generated shear flows appear to be associated with L-H transition but the trigger of the transition remains unclear
  Miki et al. PoP 19 092306

- Studies using Langmuir probes provided evidence that nonlinear exchange of kinetic energy between small scale turbulence and edge zonal flows
  Manz et al. PoP 19 072311

- Recent work on C-Mod using GPI provided a timeline for the L-H transition:
  Cziegler et al. PPCF 2014
  - First peaking o the normalized Reynolds power
  - Then the collapse of the turbulence
  - Finally the rise of the diamagnetic electric field shear

- Can the L-H transition be determined by interaction between flow and turbulence?

- Apply the velocimetry to GPI data to study the time sequence of the L-H transition on multiple discharges (NBI, Ohmic, and RF)
  ✓ Rely on velocimetry data with both high temporal and spatial resolution

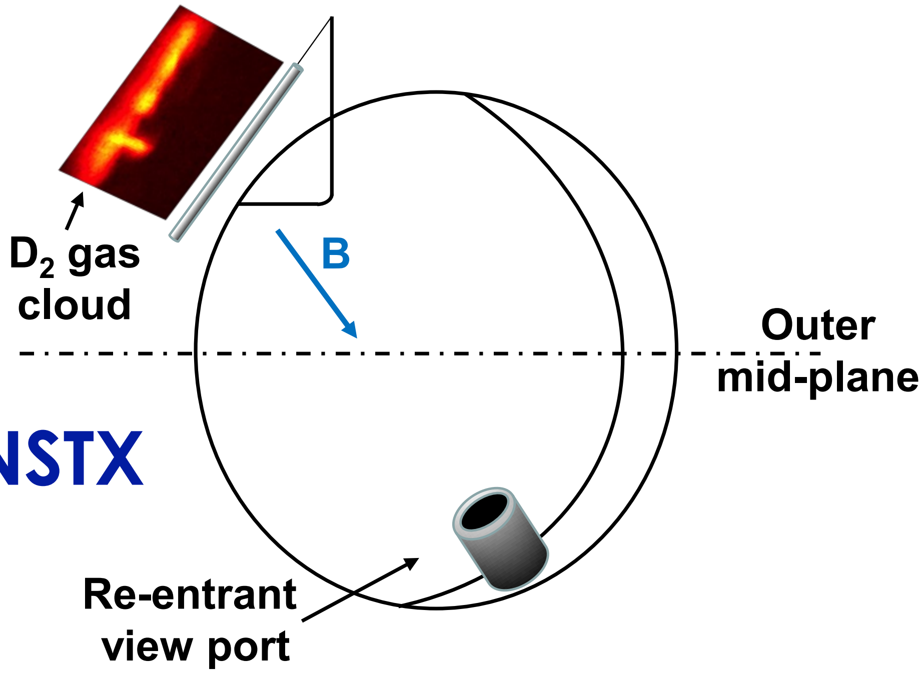
- Study the exchange of energy between the mean flow and turbulence is analyzed using the k-ε model

Approach: Summary of analysis details

- GPI data taken at ~400 kHz frame rate; Image size 24 x 30 cm
- GPI gas has minimal effects on the plasma parameters
- Analysis included RF, Ohmically, and NBI heated plasmas
- Analysis spans three regions
  - R_{edge} : Well inside separatrix and representing the plasma edge
  - R_{sep} : Around the separatrix position
  - R_{sol} : Low density region well outside the separatrix
- Note: uncertainty in location of separatrix +/- 1 cm

Discharges characteristics:
NBI-Heated: 138113:138119
Ohmically-Heated: 141745:141751
RF- Heated: 141919:141922, 142006

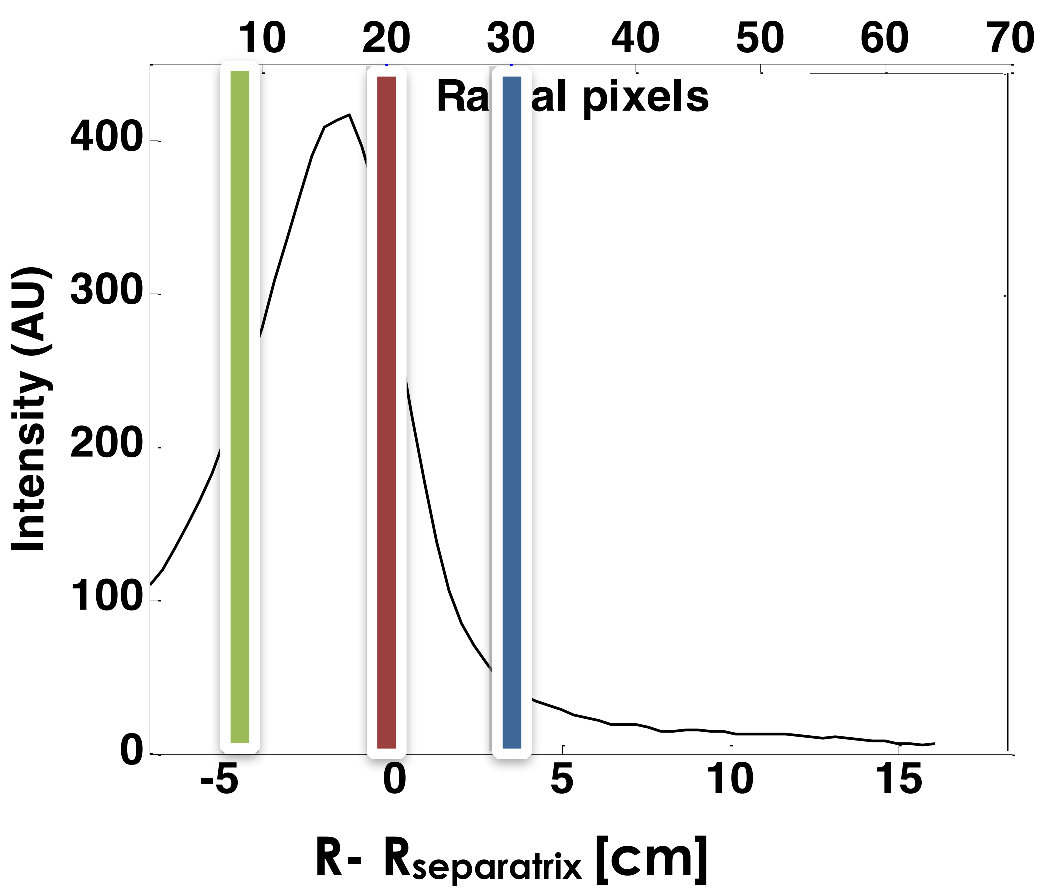
GPI Setup in NSTX

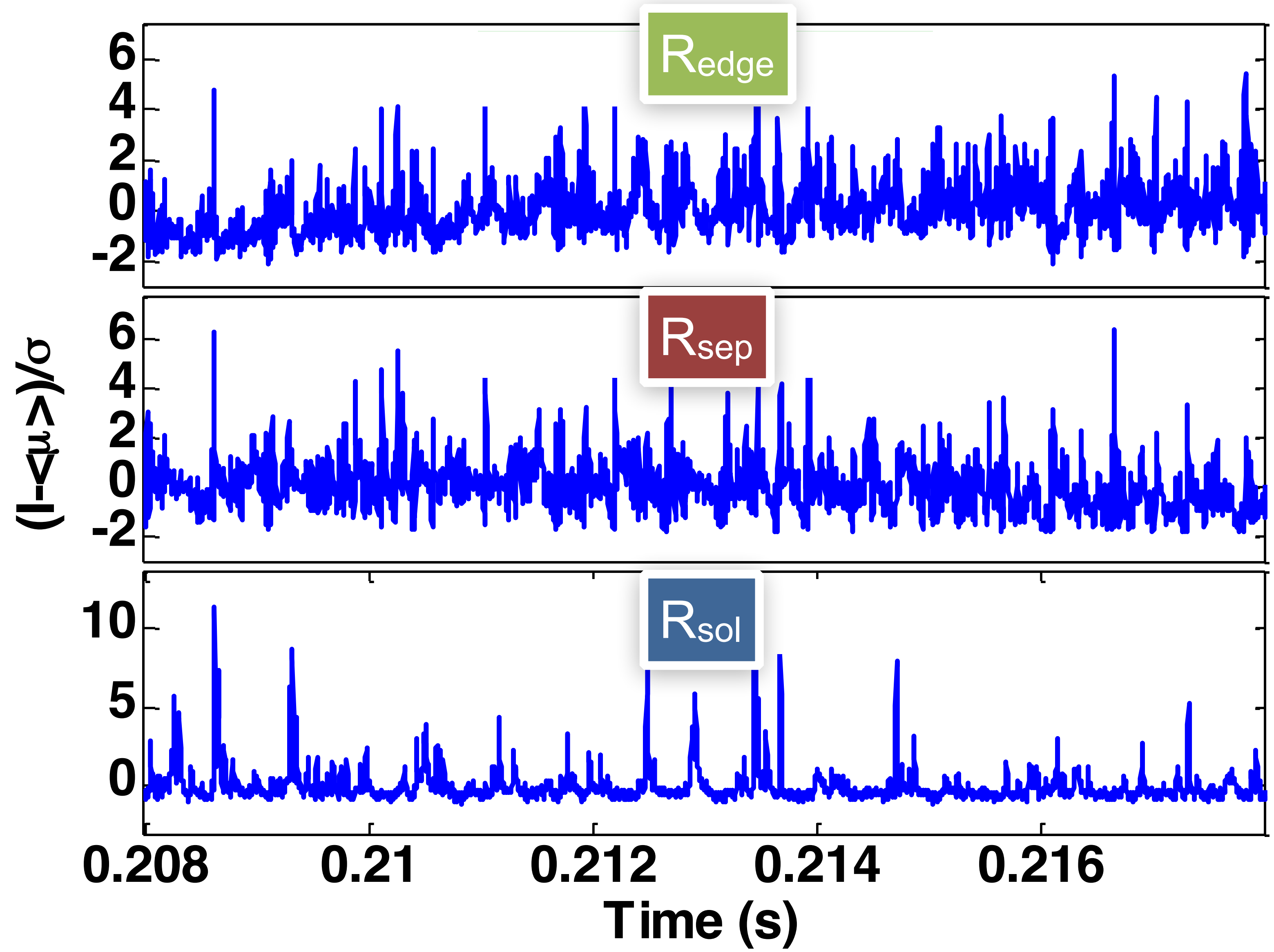


The three regions of the GPI signals exhibit different statistical characteristics

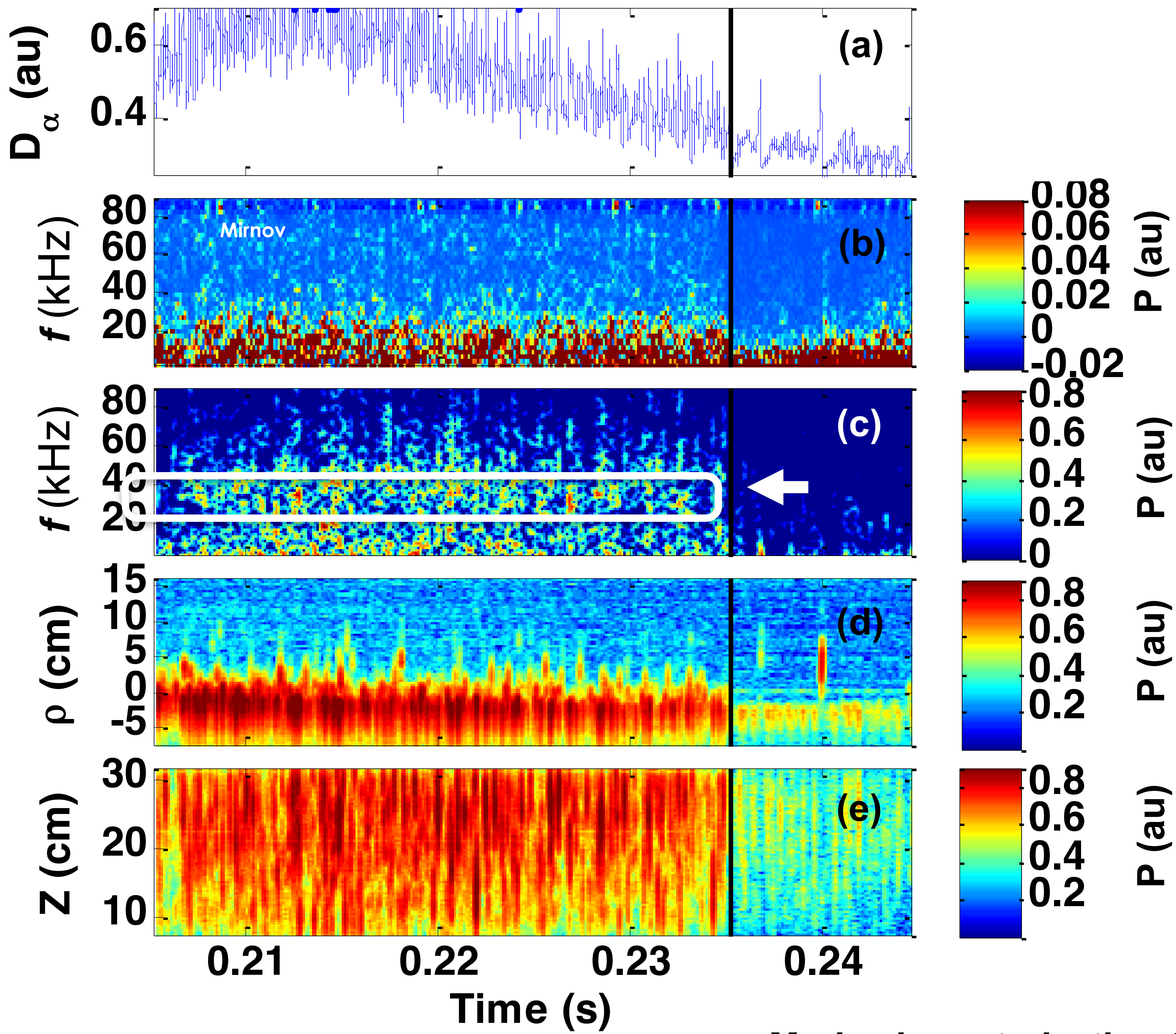
- R_{sol} signal is characterized by bursty fluctuations

- Bursty behavior is generally associated with blobs





Observation of a quasi-coherent mode with no detectable magnetic signature; the mode is localized in the density gradient



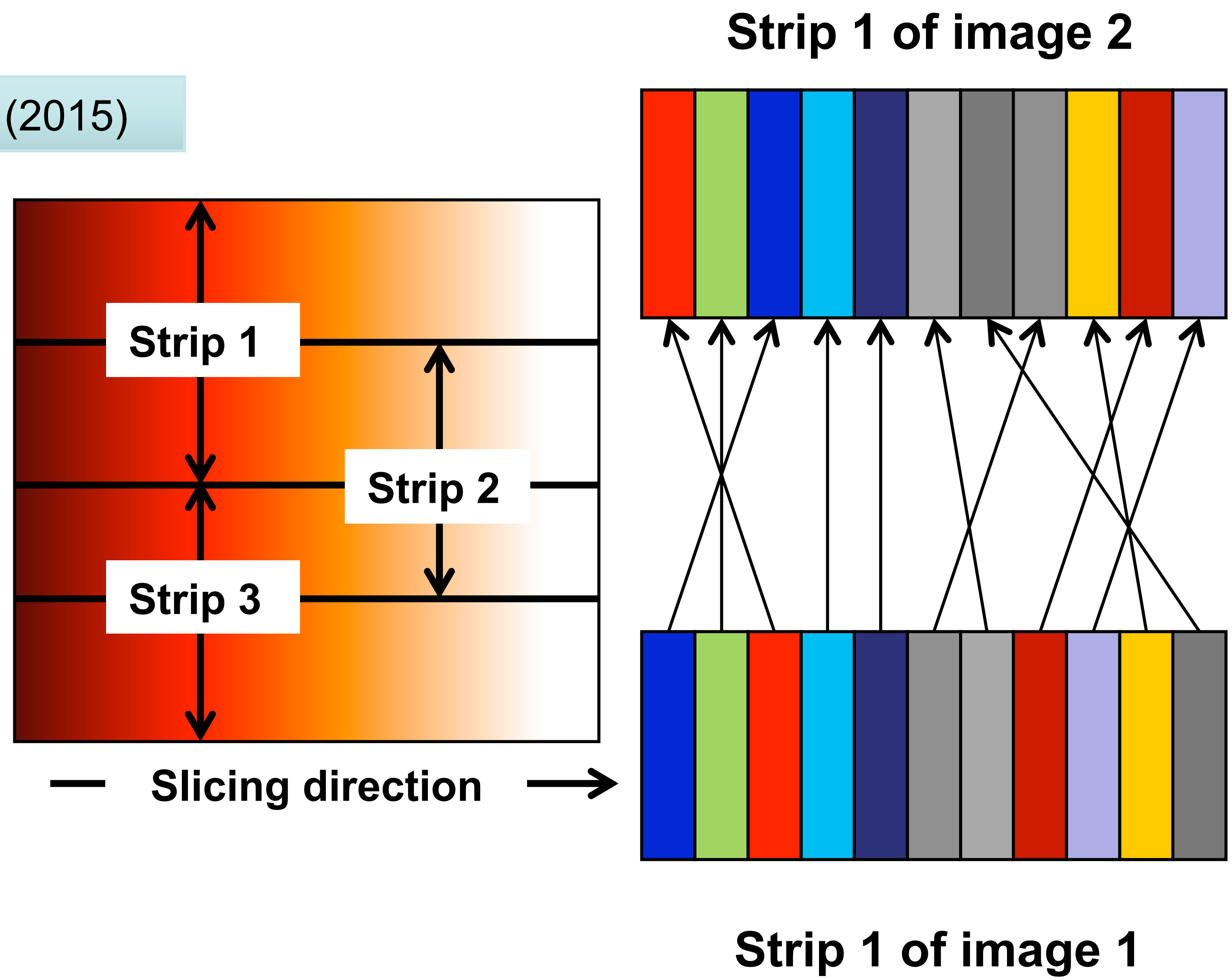
- Quasi-coherent mode is not detected on the Mirnov coils
  - Mode is either electrostatic or magnetic signature is too weak to be detected
- Mode is localized in the steep density (intensity) gradient
  - peaking at ~1.7 cm inside the separatrix

Mode characterization:S. Banerjee, in preparation PoP 2015]

Implementation of imaging velocimetry using orthogonal dynamic programming (ODP) on GPI data

S Banerjee *et al.*, Rev. Sci. Instum. **86**, 033505 (2015)

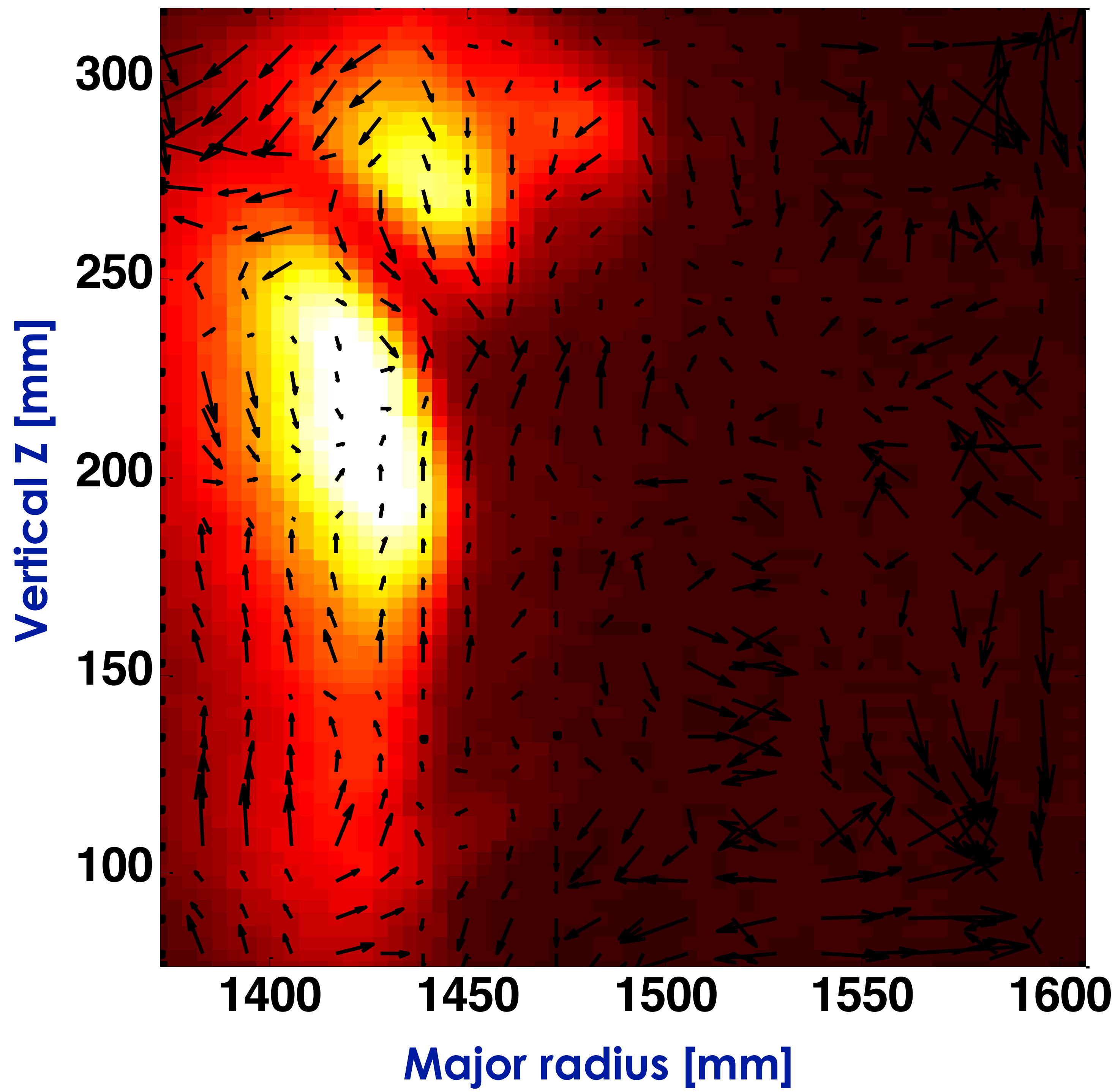
- Images are divided into parallel strips, or vectors
- Transformation from one time step to another determines basis for inferred velocity field
  - ODP leads optimal transformation with good temporal resolution
- ODP enables to reconstruct a 2D velocity field



Thus *v*(*r*, ϑ, *t*) ~ *v*(*R*, *Z*, *t*) can be obtained

Imaging velocimetry enables a time-resolved analysis of the turbulent velocity field from GPI images

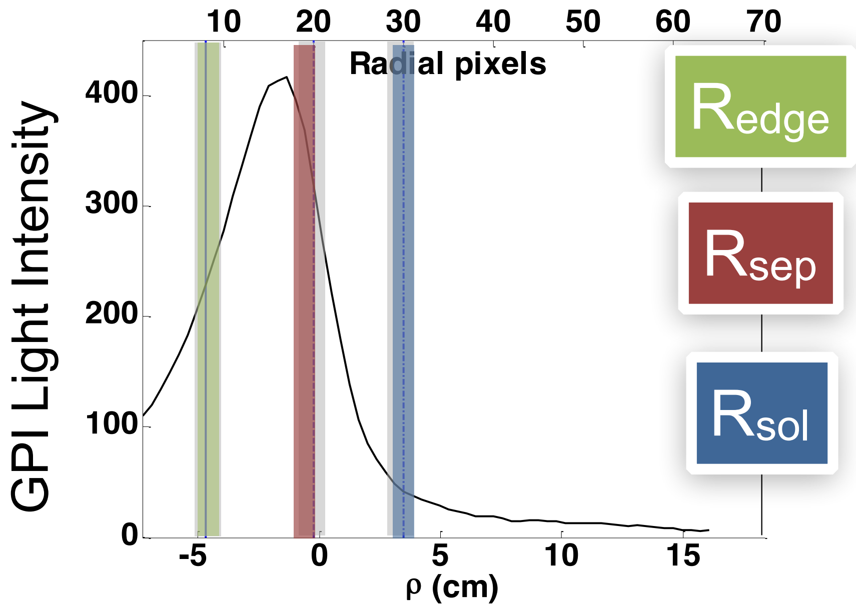
- Overlayed are the velocity field and the GPI intensity



Approach for the decomposition of the velocity field components

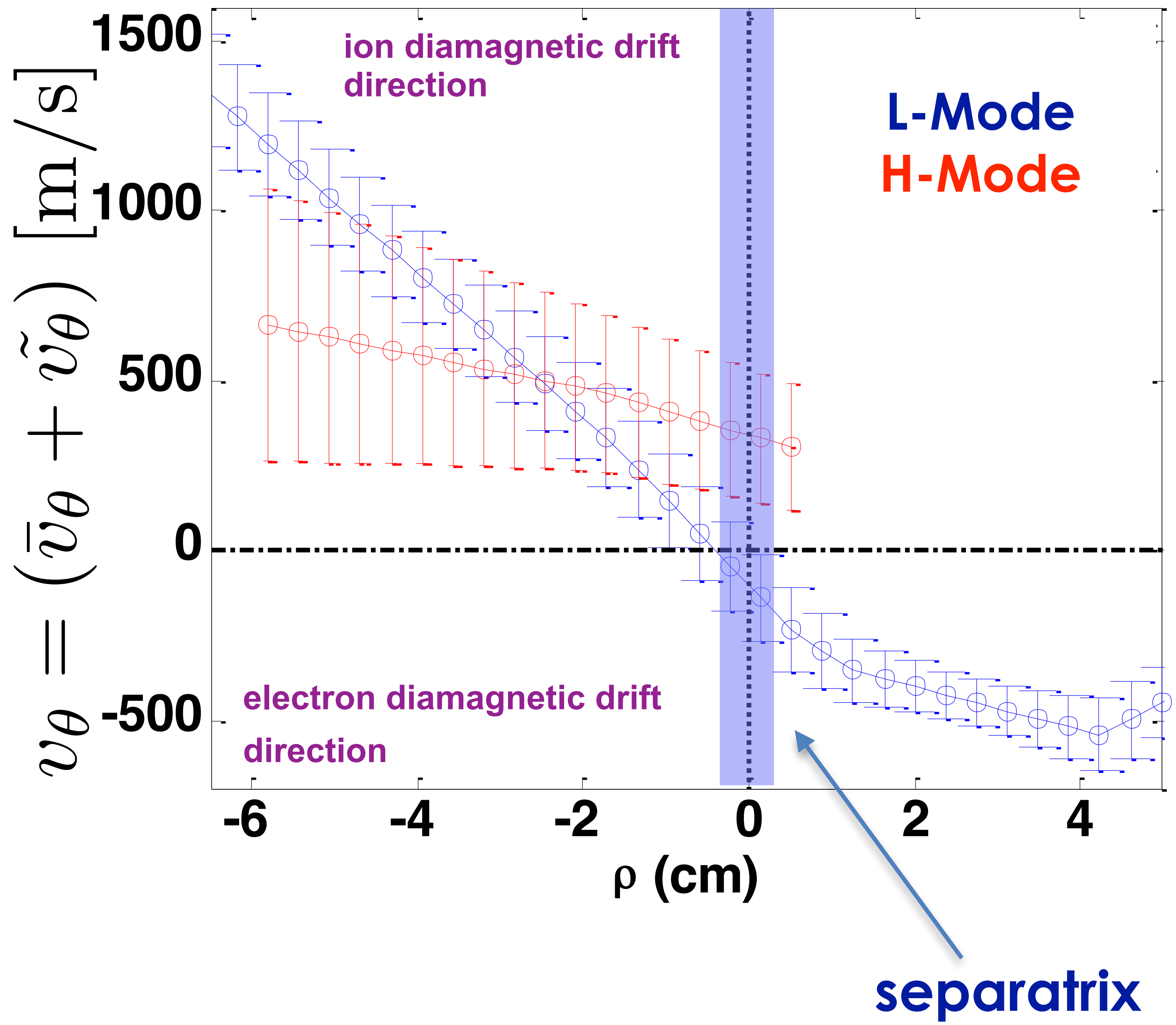
- For each velocity component, we decompose it in mean and fluctuating components
  - ➡Mean velocity $\Rightarrow$ low-pass filter up to 3 kHz $\longrightarrow < \bar{v_\theta} >$
  - ➡Fluctuating part $\Rightarrow$ high pass filter at 5 kHz $\longrightarrow < \tilde{v_\theta} >$
- L-H transition time is given by the drop in GPI intensity
- Analysis is applied to three types of discharges:
  - ➡NBI: 138113:138119
  - ➡Ohmic: 141745:141751
  - ➡RF:141919:141922, 142006

Application of the ODP-based velocimetry for L-H transition analysis



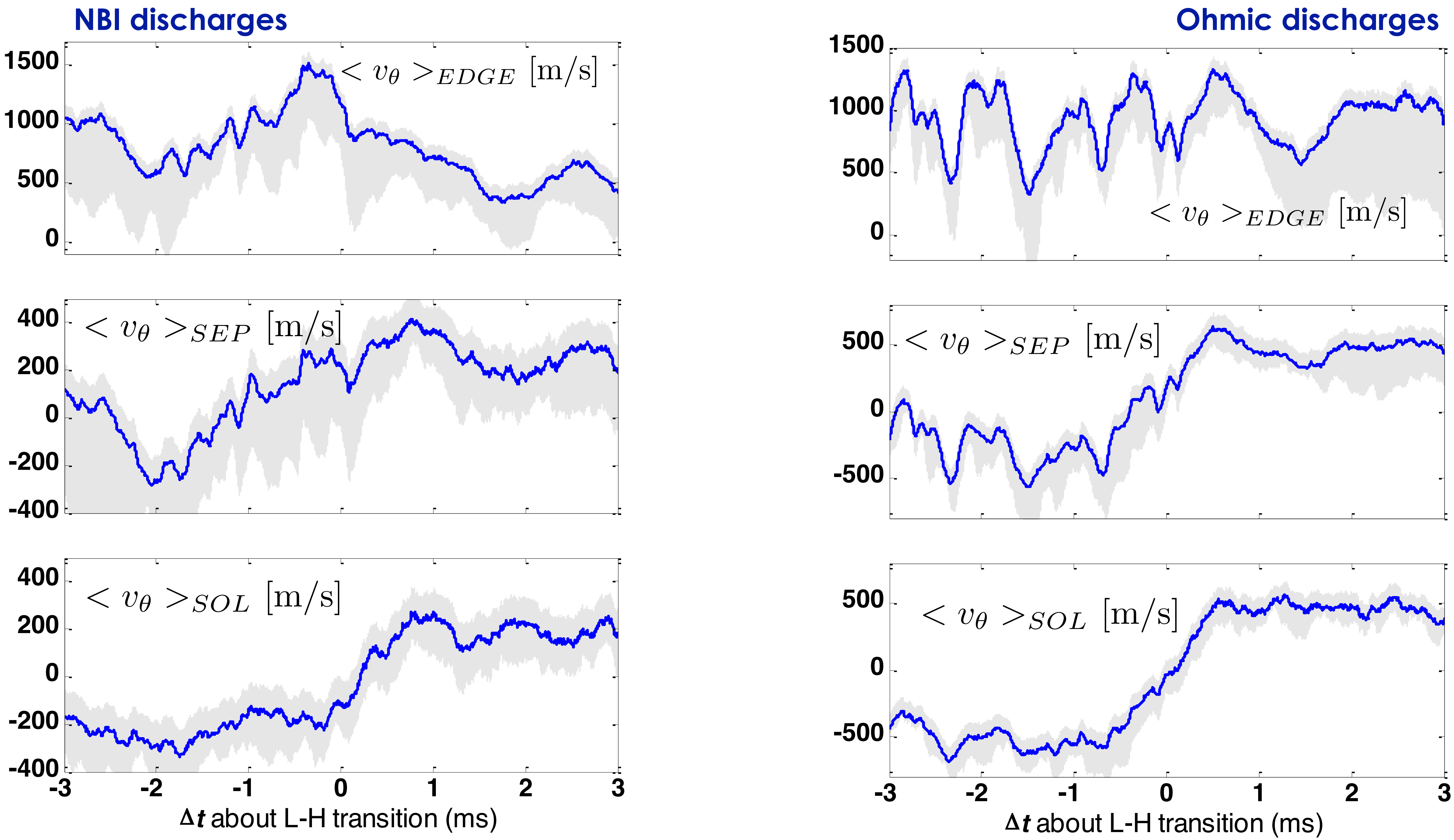
- Two phases are distinguished: L- and H-modes
- The mean is determined using chunks of 10 ms
  - Clear change of V_θ in the SOL
- Errorbars represent the std between the 10 ms chunks

Radial profiles of the poloidal velocity averaged for all ohmic shots



In L-mode, there is clear transition of the direction at the separatrix of the turbulent flow

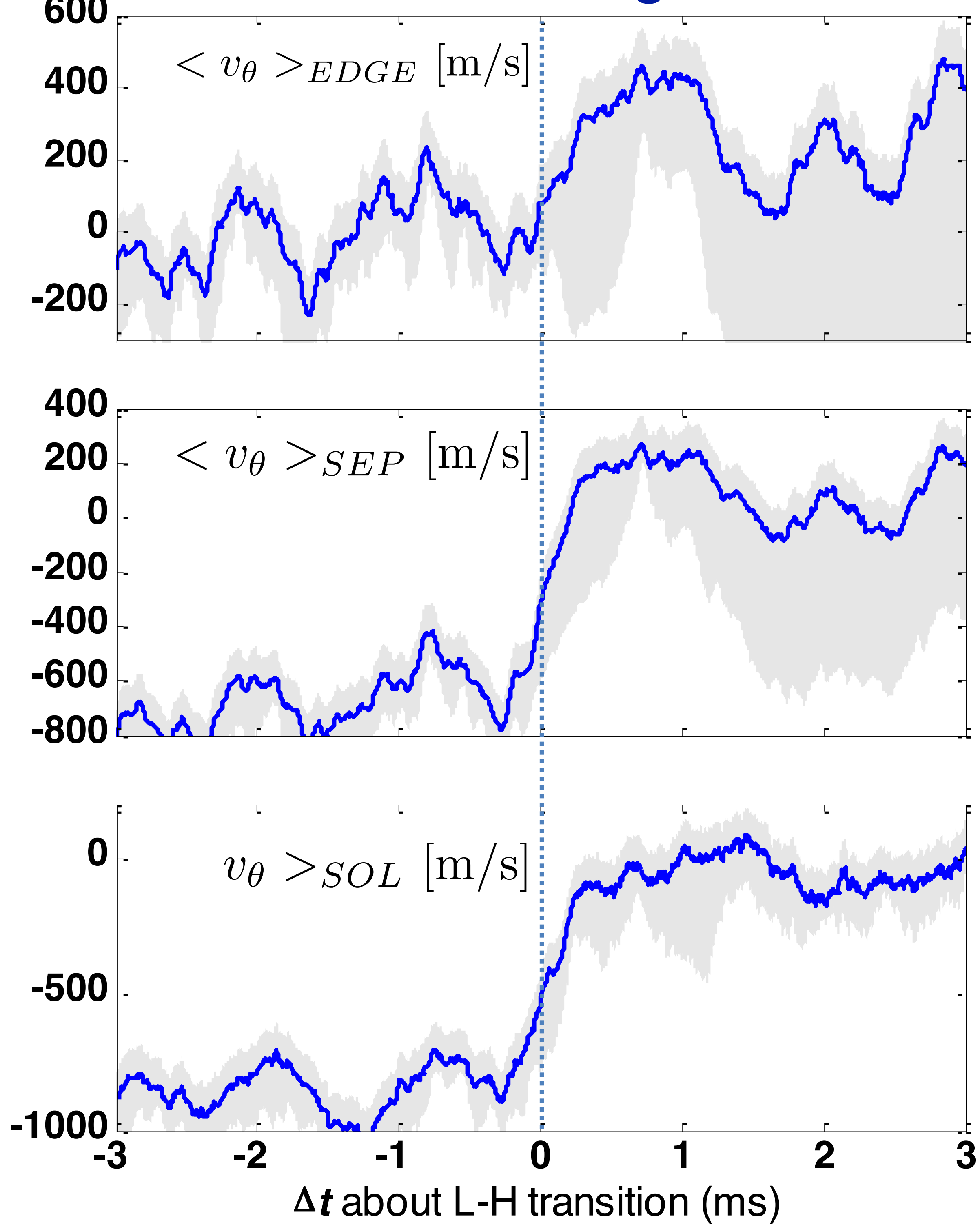
Time history of the bulk poloidal velocity across the L-H transition at different radii



Clear drop in velocity inside the separatrix consistent with an increase of the edge shear

The rapid increase across the L-H transition of the bulk poloidal velocity in the RF cases in NSTX is similar to that observed in C-Mod

RF Discharges in NSTX



C-Mod

Cziegler Plasma Phys. Control. Fusion **56** (2014) 075013

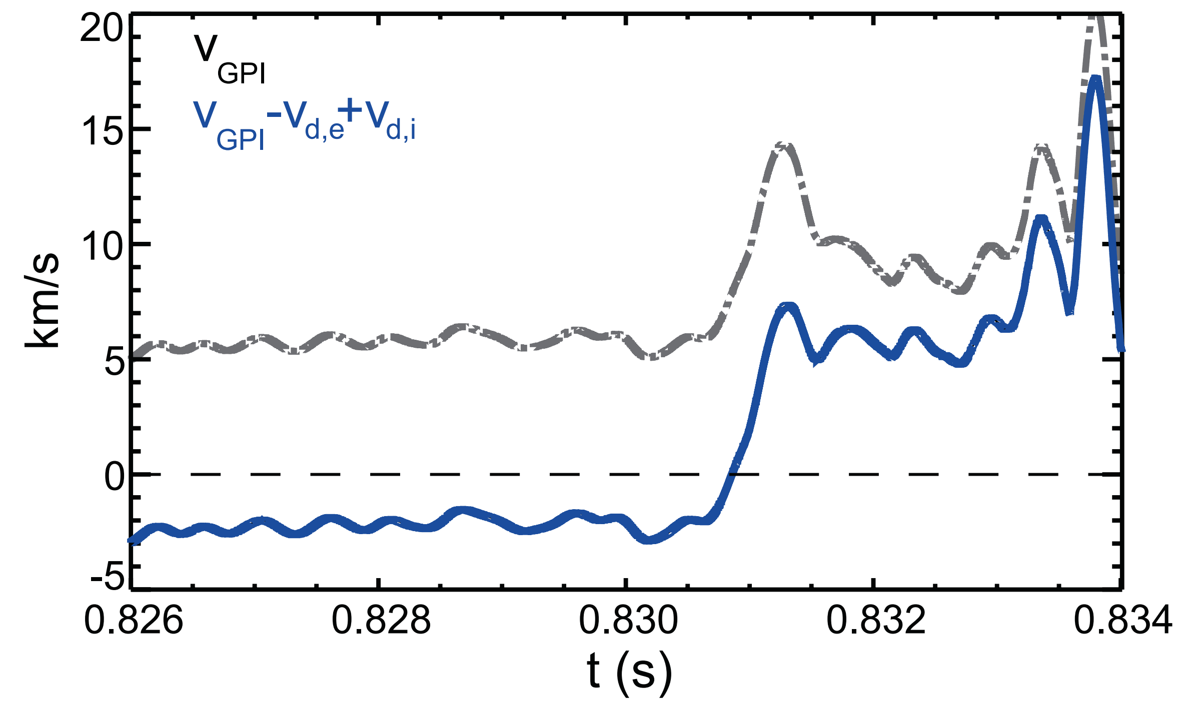
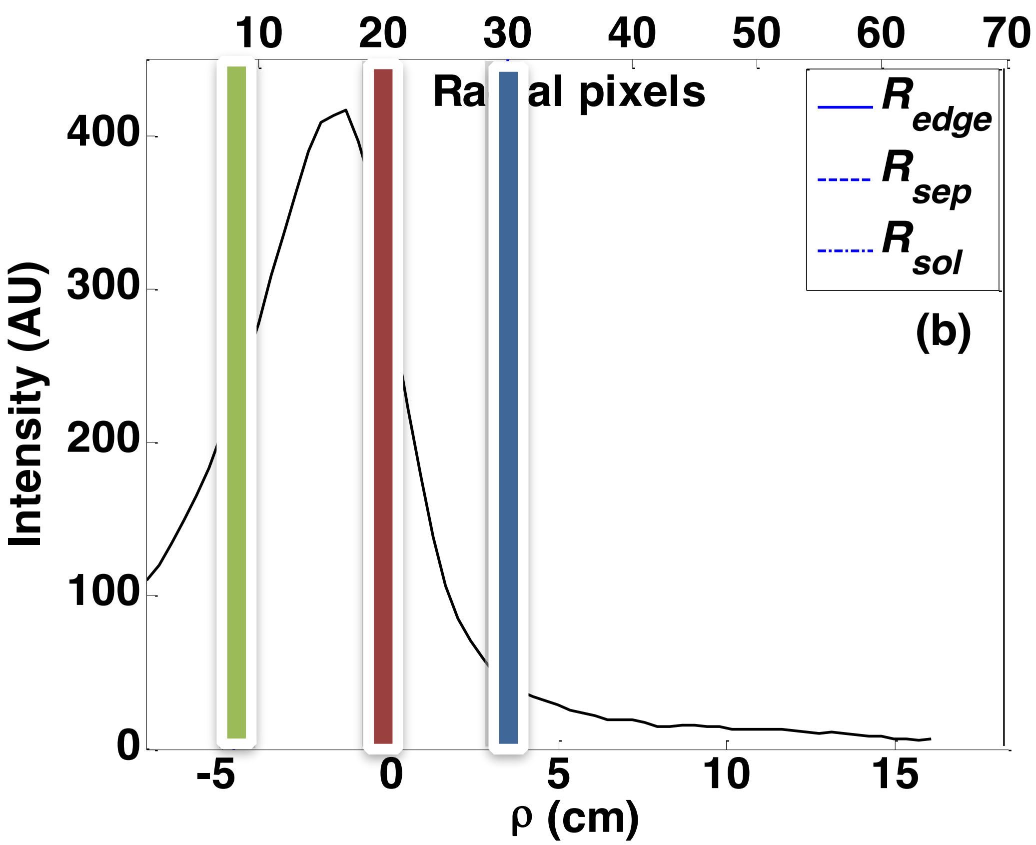
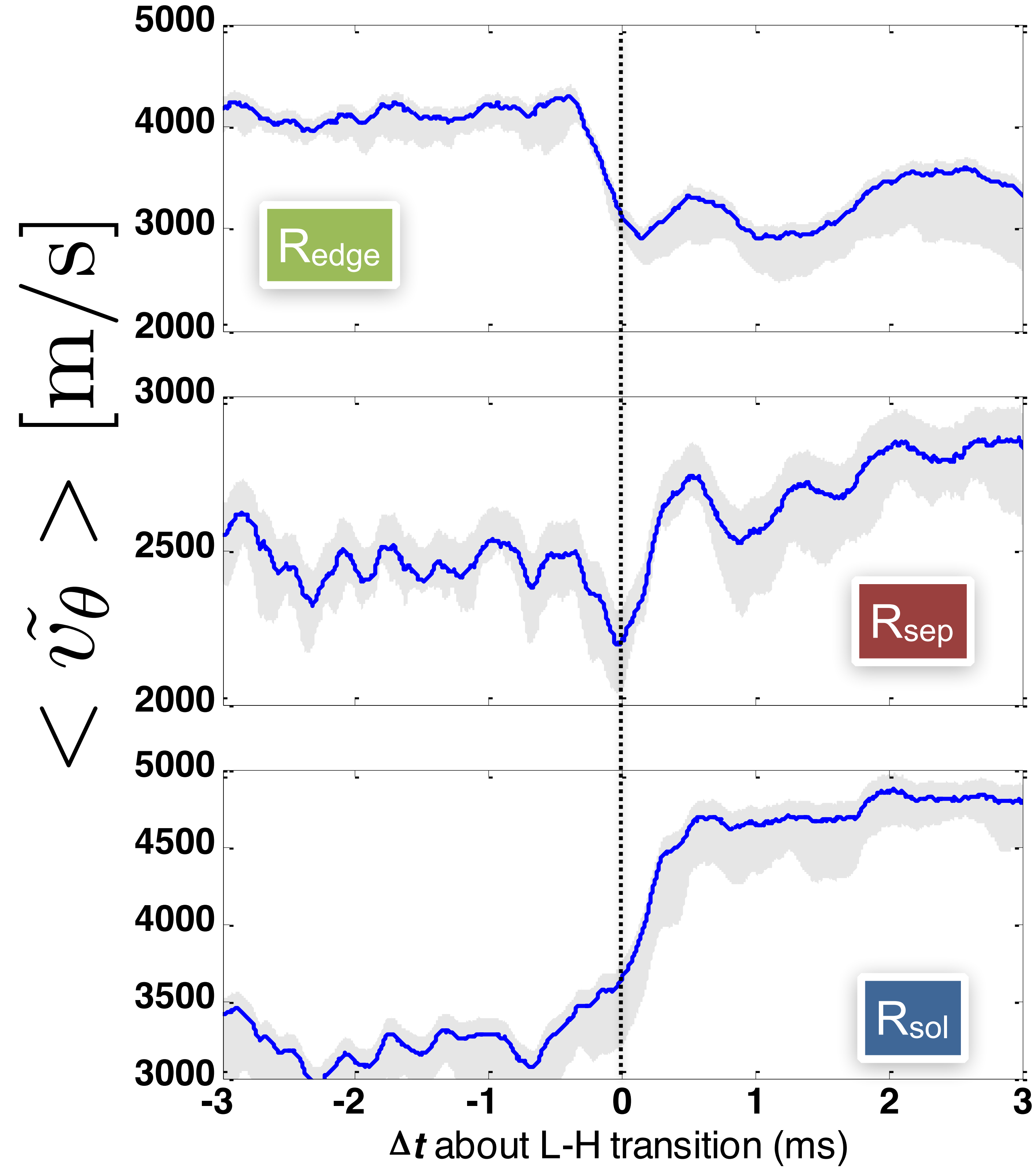


Figure 5. Estimated bulk poloidal velocity based on GPI velocimetry corrected with diamagnetic terms calculated from TS and ECE measurements.

- This appears to suggest that during the L-H transition the velocity shear steepens

Analysis of the time-dependent velocities across the L-H transition for three regions





- Temporal resolution of 250 μs is determined by the moving average
- The poloidally averaged v_θ shows a sharp change at both R_{sep} and R_{sol}
- However, v_θ drops at R_{edge}

The exchange of energy between the mean flow and turbulence is analyzed using the k-ε model: Description

- It is well-documented that during the L-H transition, a sheared flow at the edge is established.
- The velocimetry analysis is extended to investigate the interaction between mean flow and turbulence.

$< ... >$ means poloidaly averaged.

$\mathbf{v} = \bar{\mathbf{v}} + \tilde{\mathbf{v}}$ Reynolds decomposition

$P = \frac{1}{2} < \tilde{v_\theta} \tilde{v_r} > \frac{\partial < \bar{v_\theta} >}{\partial r}$ Mean flow production term

$\tilde{K} = \frac{1}{2} < \tilde{v_\theta}^2 >$ and $\bar{K} = \frac{1}{2} < \bar{v_\theta}^2 >$ since $v_\theta \gg v_r$

P. Manz *et al.*, POP **19**, 012309 (2012)
I. Cziegler *et al.*, NF **55**, 083007 (2015)

$\tilde{T} = < \tilde{v_r} \tilde{v_\theta} > < \tilde{v_\theta} >$ and $\bar{T} = < \tilde{v_r} \tilde{v_\theta} > < \bar{v_\theta} >$

Model equations underlying the data analysis strategy

$\partial_t \tilde{K} = -\gamma_{eff} \tilde{K} - P - \partial_r \tilde{T}$ and $\partial_t \bar{K} = -\partial_r \bar{T} + P + \nu_{LF} \bar{K}$

Reynolds Work

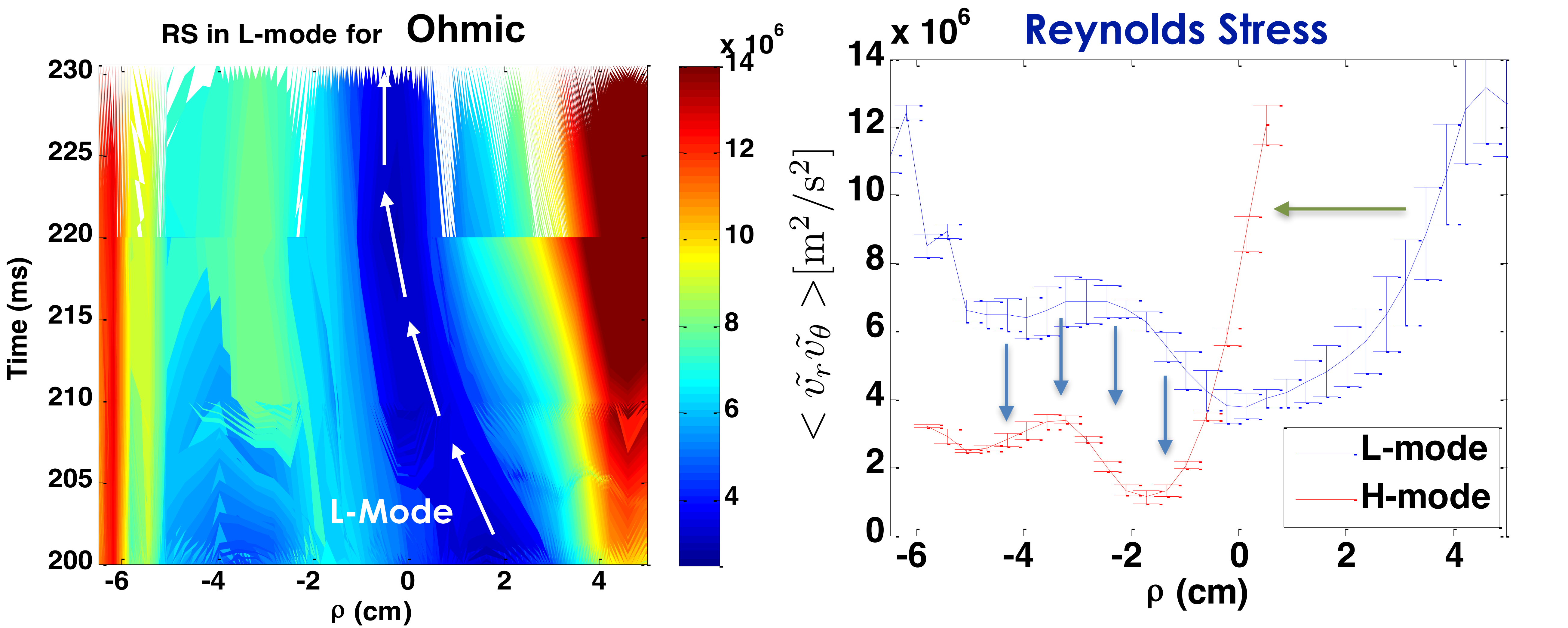
Damping rate of the low-frequency flow

Net effective linear growth

total loss of local kinetic energy

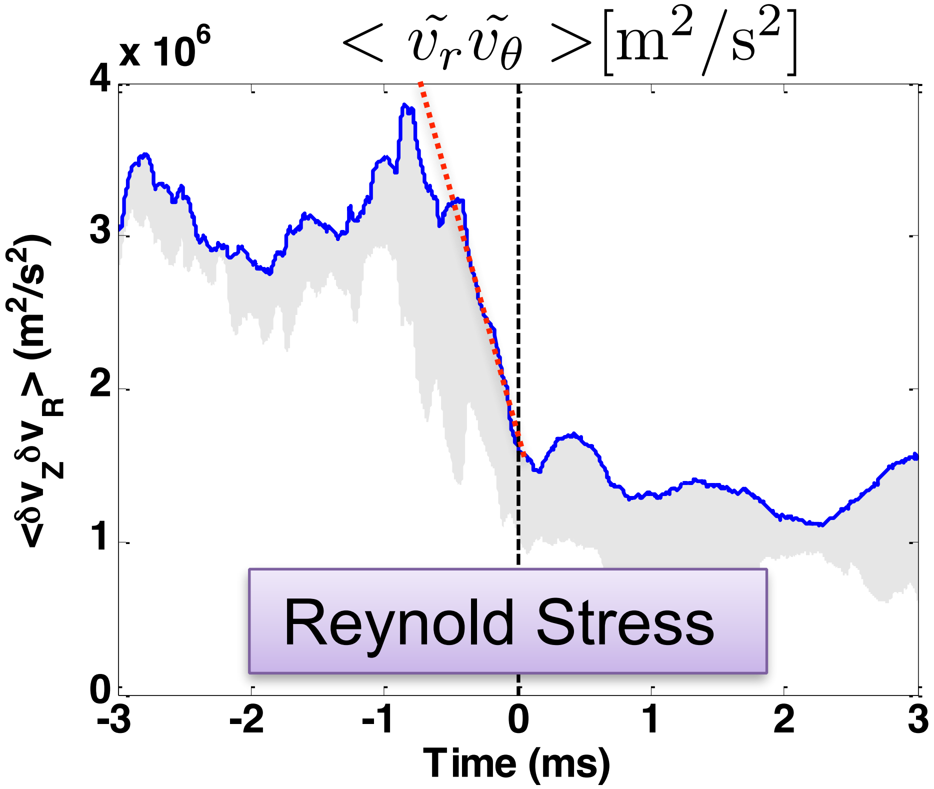
Time and spatial evolution of the Reynolds stress indicate a shift of the maximum stress towards the separatrix near the L-H transition

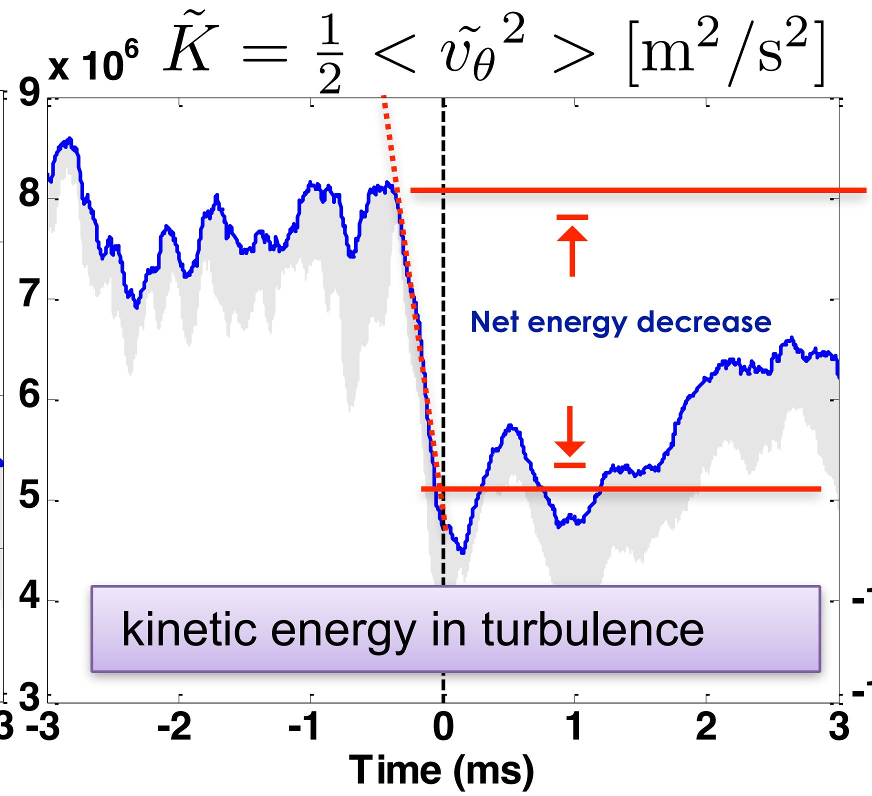
The Reynolds stress is expected to be reduced as one transitions to the H-mode
Clear increase of the radial gradient of the Reynolds stress in the H-mode phase

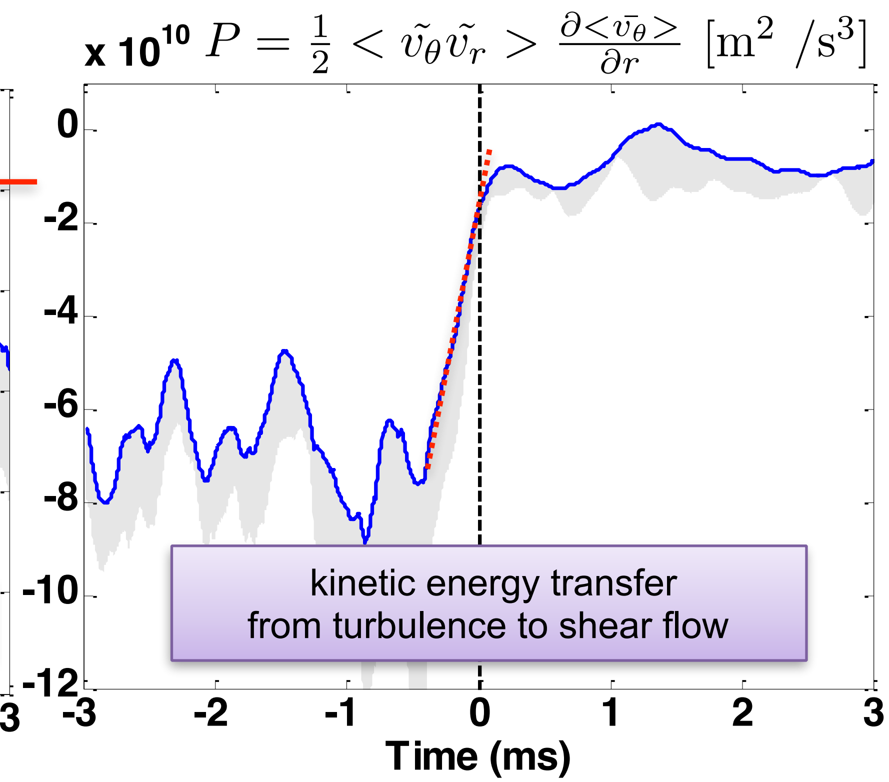


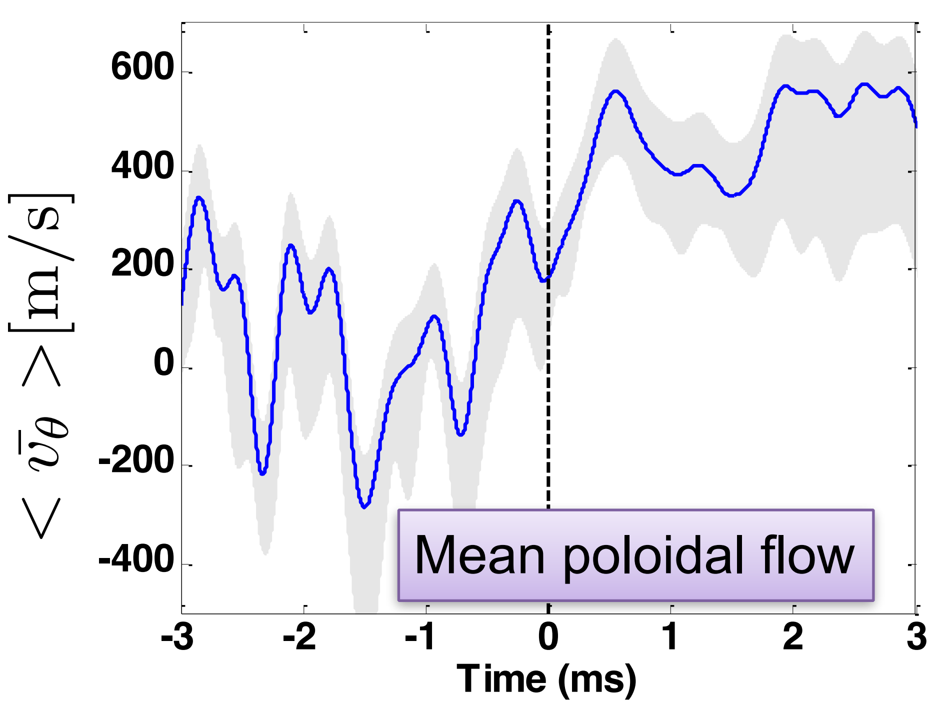
- Work is in progress to understand the implications of such radial shift
- This observed reduction of Reynolds stress is in contradiction with observations in ohmically heated discharges in HT7 Xu Phys. Rev. Lett. 84, 3867 (2000).

Evolution of the turbulent energy transfer parameters at 1 cm ± 4 mm inside separatrix: Ohmic Discharges





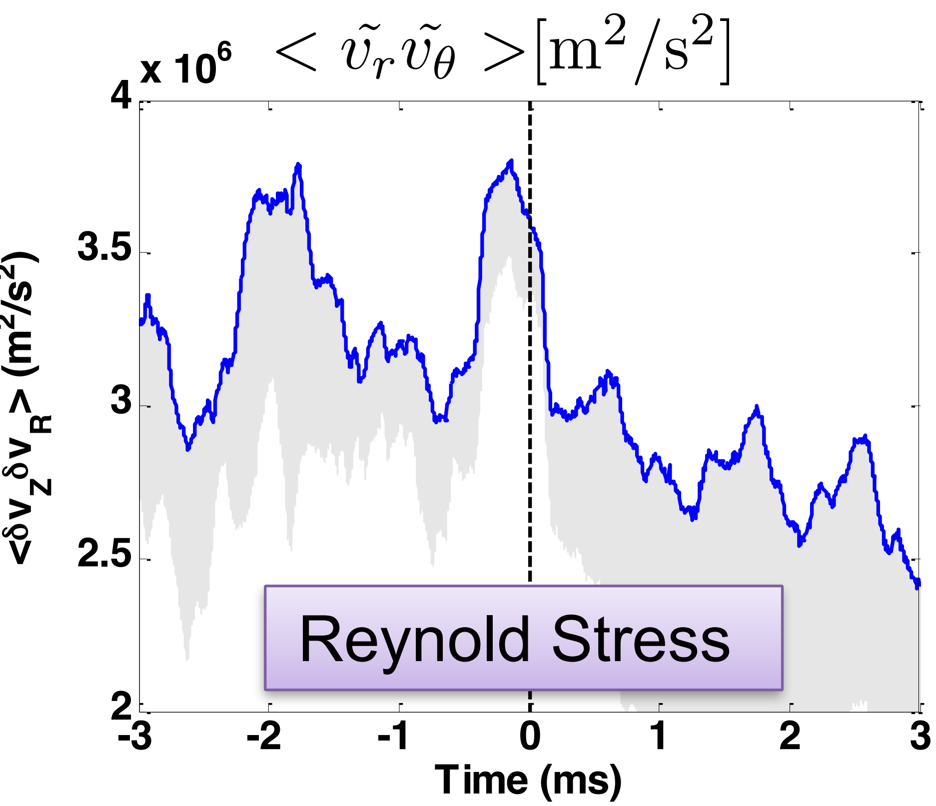


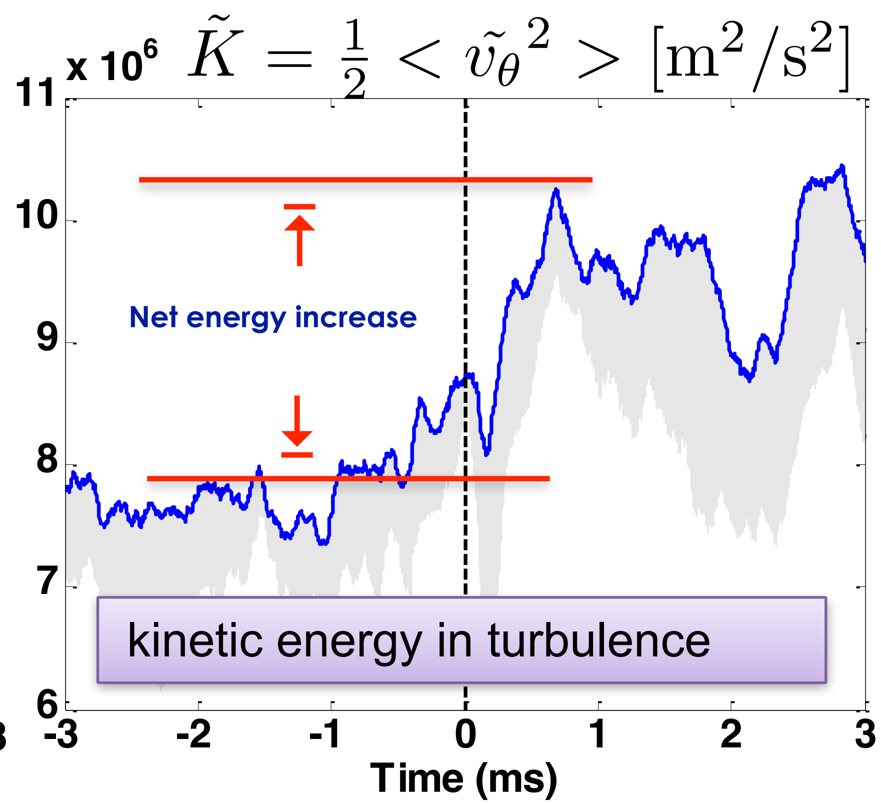


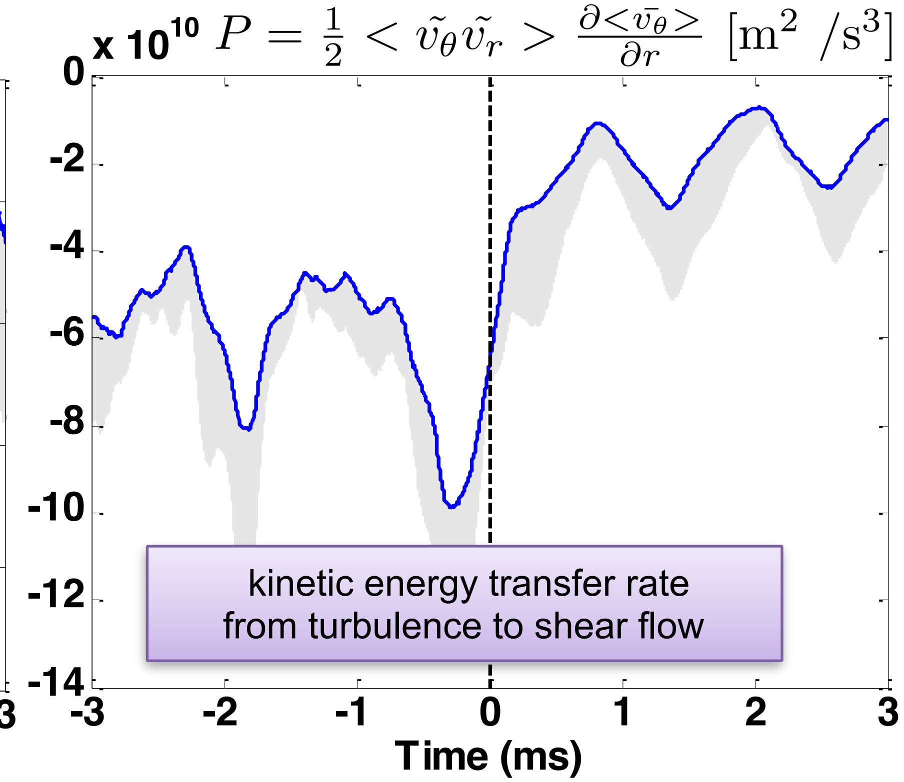
- The decrease of the Reynolds stress appears to precede the reduction of the kinetic energy in the turbulence

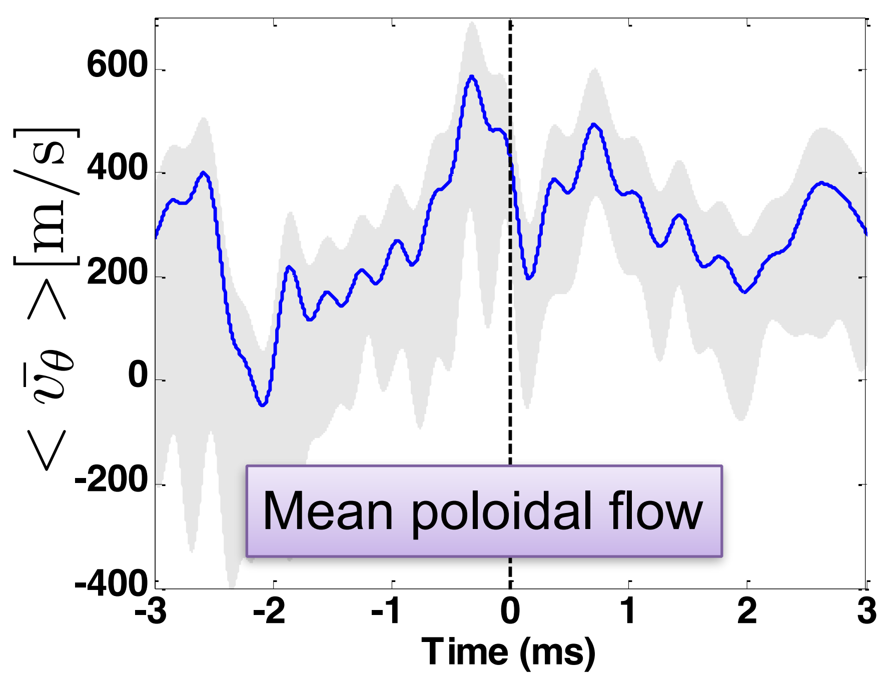
- Increase of the production term is **consistent** with a drop in kinetic energy of the turbulence.
  - Production term increase is also associated with an increase of the mean flow

The kinetic energy in the turbulence increases across the L-H transition, while the mean flow drops for NBI Discharges



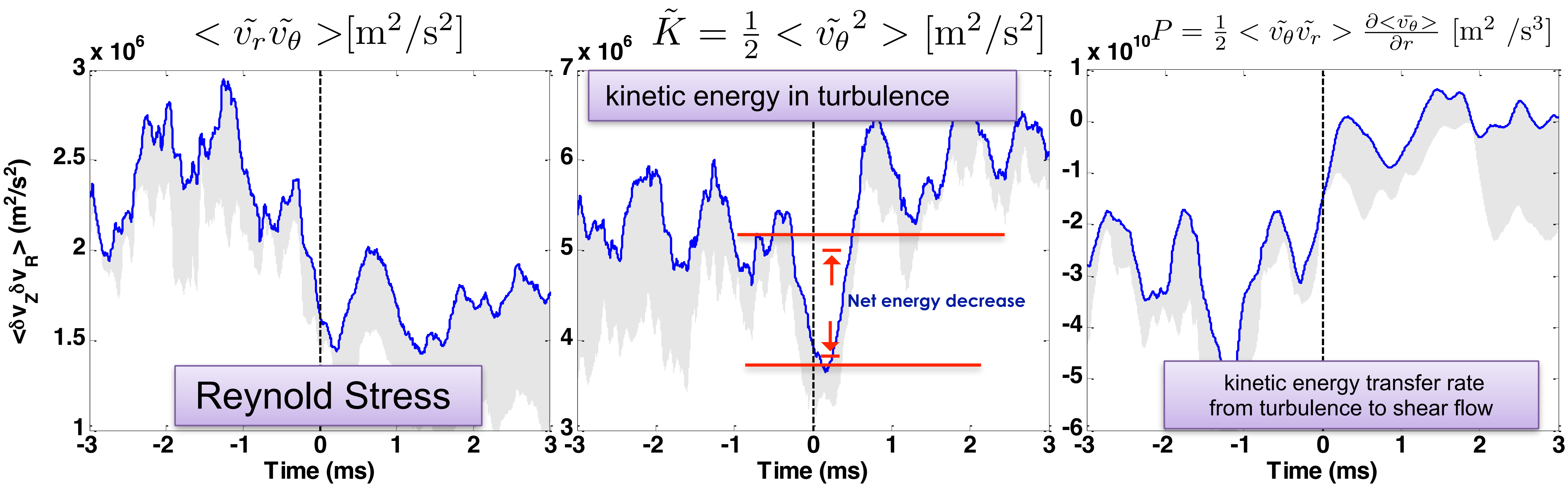






- Production term is inconsistent with an increase of the turbulence kinetic energy
  - Hypothesis: There might also be an increase of dissipation to small scale turbulence
- Local fluid flow does not appear to change during the L-H

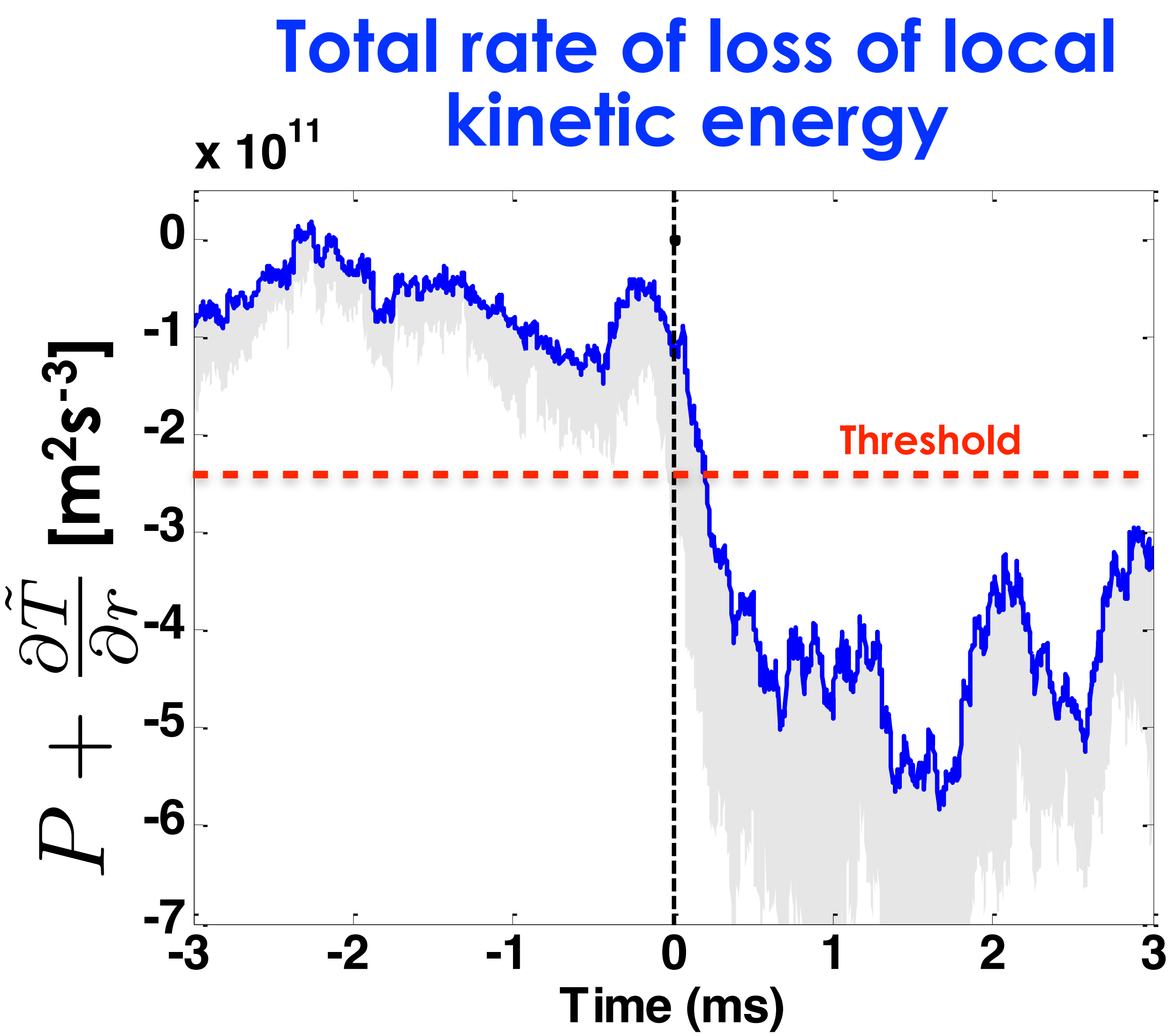
Similar to Ohmic discharges, RF discharges also show a drop of the kinetic energy in the turbulence across the L-H transition

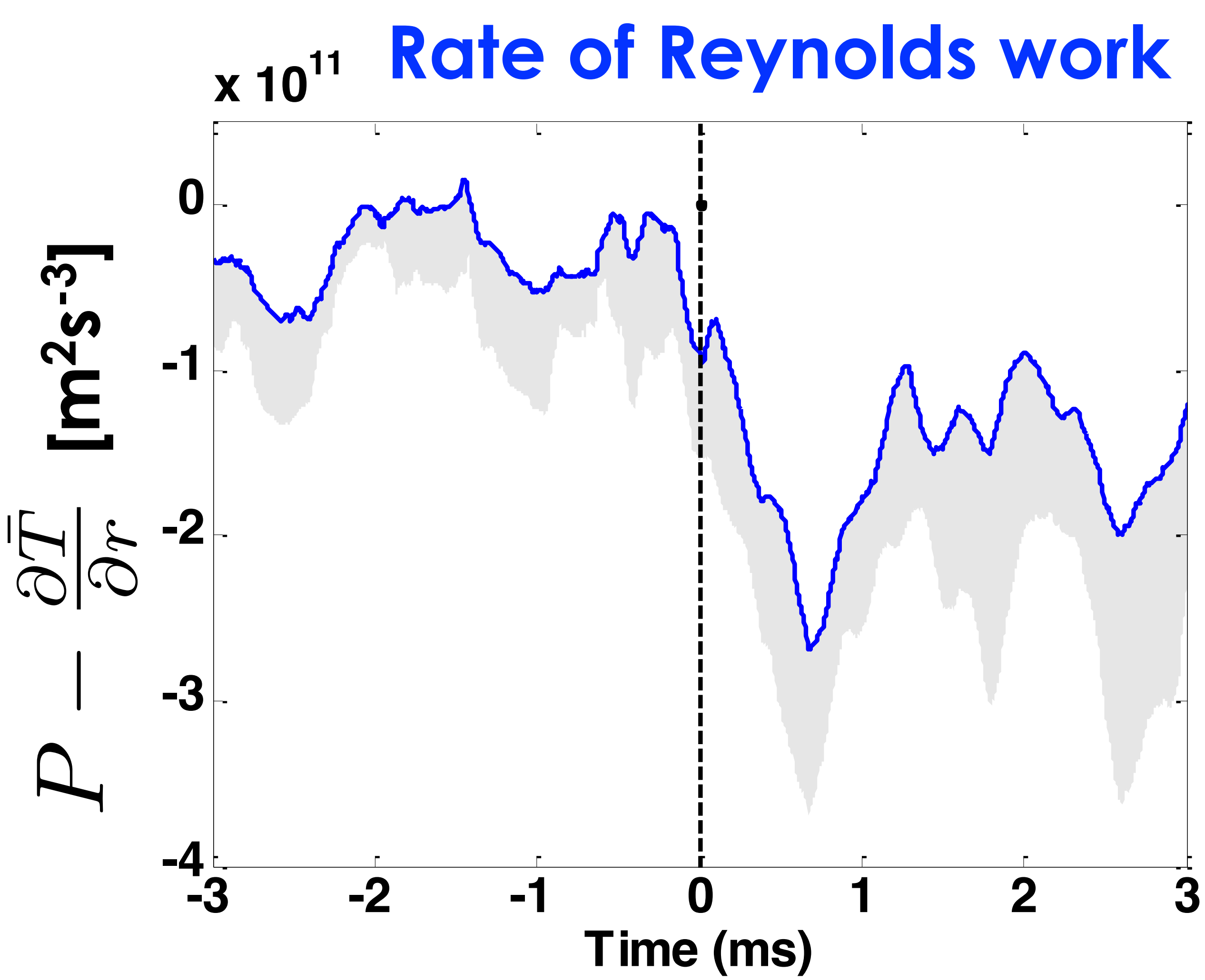


- The decrease of the Reynolds stress correlates with the reduction of kinetic energy turbulence

- Increase of the production term is **consistent** with a drop in kinetic energy: Similar to Ohmic discharges
  - Suggesting that additional torque from NBI (absent in RF and ohmic) could be the main difference

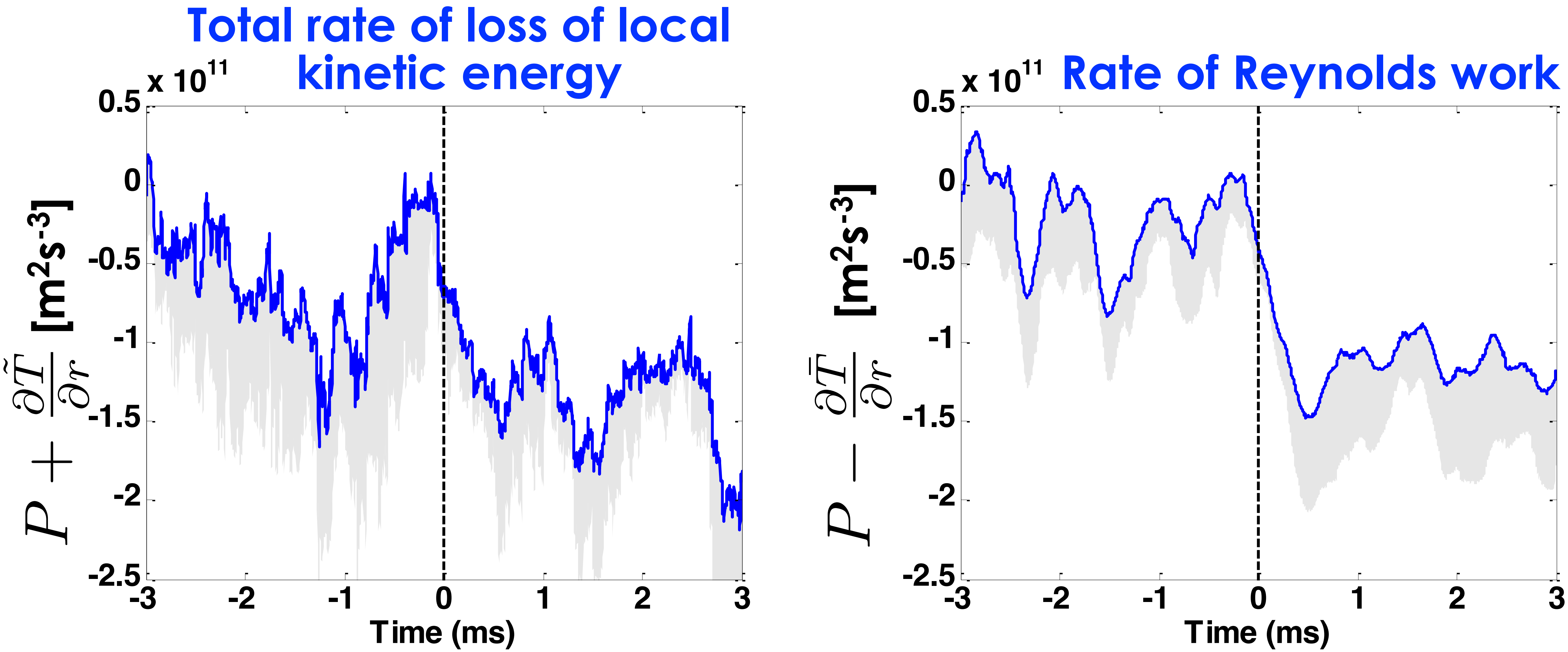
In NBI discharges, the rate of loss of kinetic energy from turbulence clearly exceeds the fluctuation driven flow





This rather strong rate of loss of local kinetic energy is consistent with a **strong** collapse of turbulence in the L-H transition

In Ohmic discharges on the other hand, the rate of loss of kinetic energy from turbulence matches the fluctuation driven flow



This suggests an efficient conversion of kinetic turbulence to flow drive during the L-H in Ohmic discharges.

Summary

- Observation of drift-like quasi coherent mode at 40 kHz preceding the L-H transition
  [S. Banerjee, in preparation 2015]
  - Mode appears to be localized near the separatrix
  - Due to a lack of magnetic signature on the Mirnov, the mode is likely to be electrostatic

- Turbulence energy transfer is analyzed during the L-H transition in RF, ohmic, and NBI shots
  - Clear reduction of the radial profile of the bulk poloidal velocity in L vs H mode regimes
- In ohmic and RF, the increase of the production term is consistent with a drop in kinetic energy
  - This is NOT the case for NBI discharges as the kinetic energy in turbulence continues to increase
    - This might suggest that the additional torque from NBI could be important.
- The rate of loss of kinetic energy to the mean flow is consistent with a collapse of turbulence in the L-H transition for NBI discharges.
  - Residual loss of kinetic energy is inconsistent with flow drive.
- In ohmic discharges, however, an efficient conversion of kinetic turbulence to flow drive is observed: This is not the case for NBI L-H transition