Energy Exchange Dynamics across L-H transitions in NSTX

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Result Review
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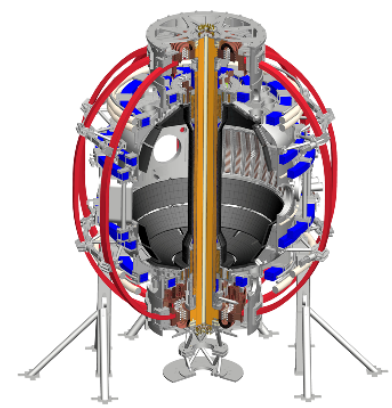

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Most models on L-H transition focus on ExB shear

- **L-H transition appears as *heating* power is increased beyond a threshold.**

- **Paradigms for the L-H transition can be summarized in two parts:**

1. **A sheared zonal E x B flow is driven**
   - Nonlinear energy transfer from turbulence to flows via Reynolds stress.
   - Diamagnetic flow shear due to ∇P_i contribution to E_r

2. **Suppression of turbulence by flow shear which could occur via two possibilities:**
   - Energy transfer to flows ***directly*** depletes the turbulent fluctuations.
   - Shearing of eddies destroy turbulence in other ways
     - Reduction of the effective growth rate
     - Increase damping

Goal: Gain deeper insights in the physics of the L-H transition by examining the energy transfer dynamics across the L-H transition in NSTX using 2D edge turbulence images

GPI diagnostic is central to the analysis

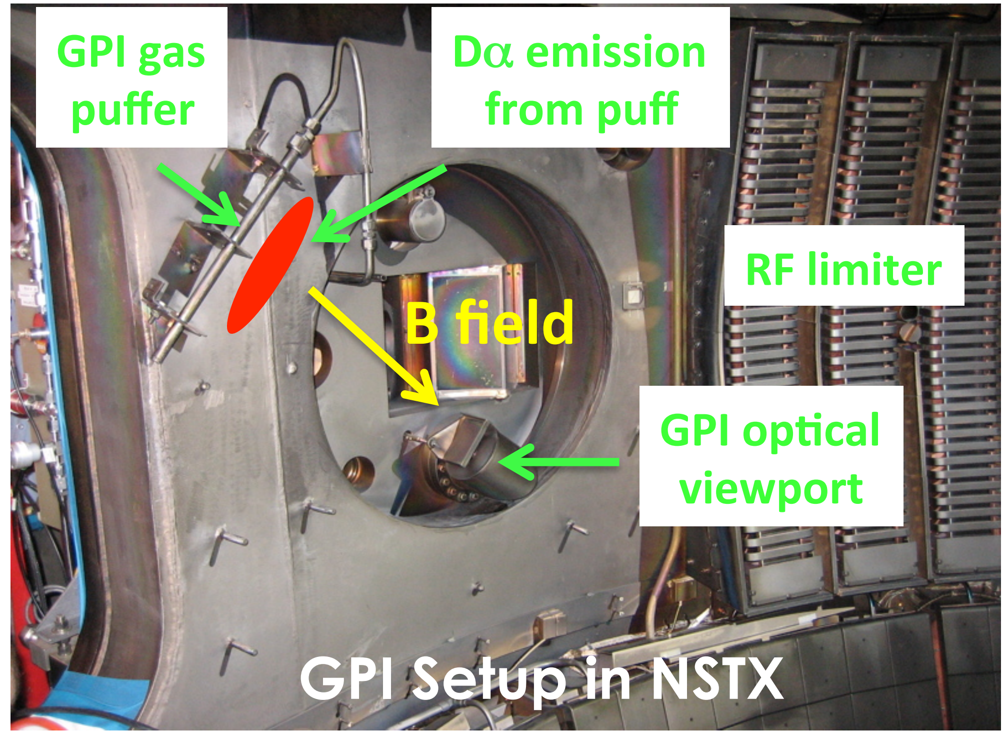
- GPI data taken at ~400 kHz frame rate;
  - Image size 24 x 30 cm
  - Spatial resolution ~ 1 cm

See Zweben et al. NF 44 134 (2004) for detailed description

- GPI gas has minimal effects on the plasma parameters

Zweben et al. PPCF 56 095010 (2014)

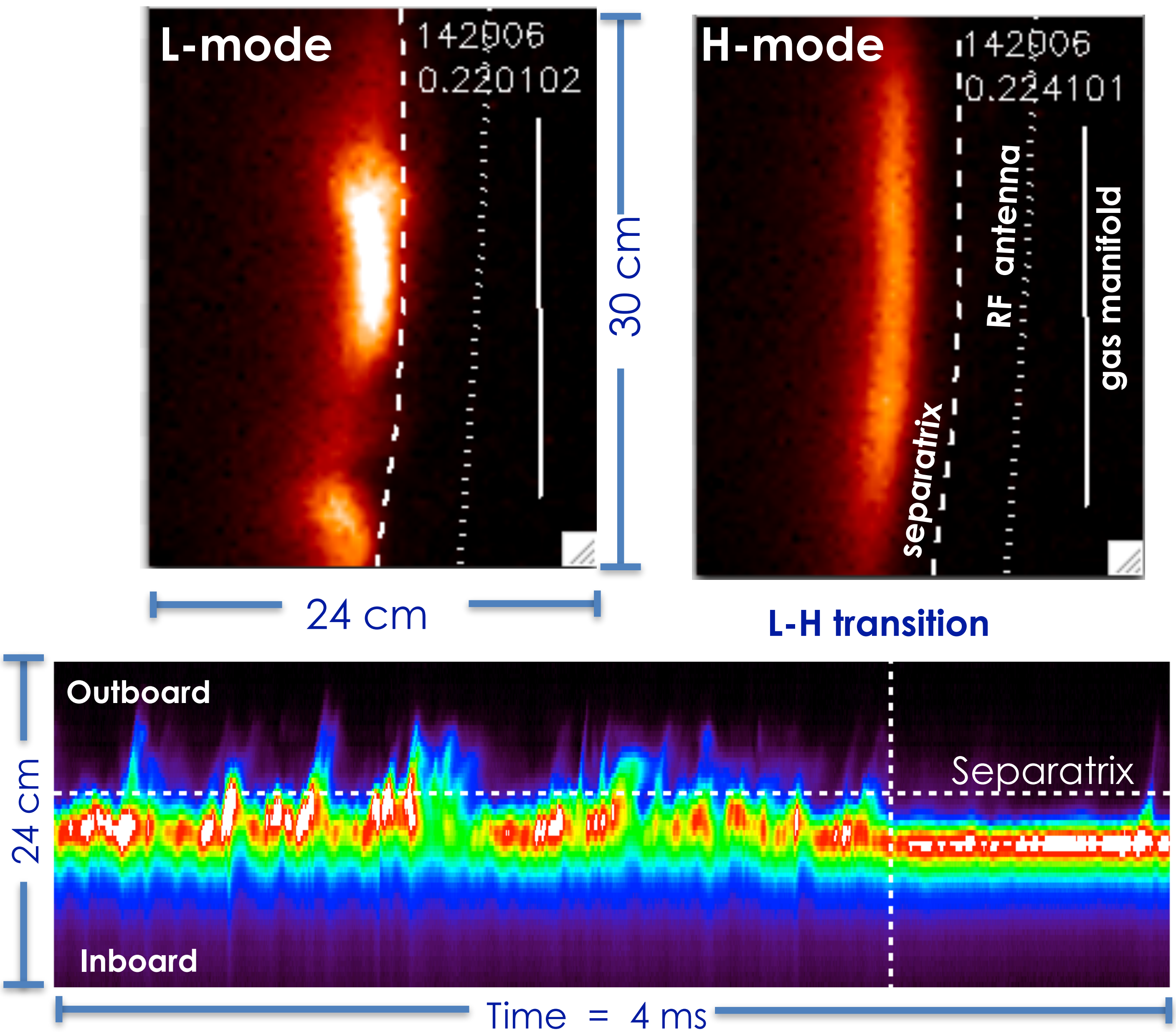
- Analysis included RF, Ohmically, and NBI heated plasmas



Discharges characteristics (total of 17):

NBI-Heated: 138113:138119
Ohmically-Heated: 141745:141751 (not shown here)
RF- Heated: 141919:141922, 142006

L-H transitions are seen as a sudden change in the edge GPI D_α emission profile

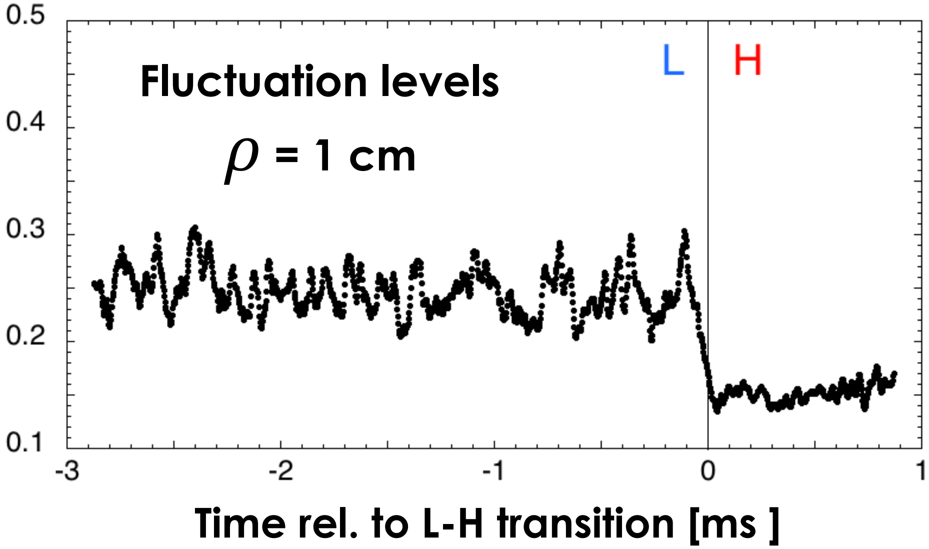


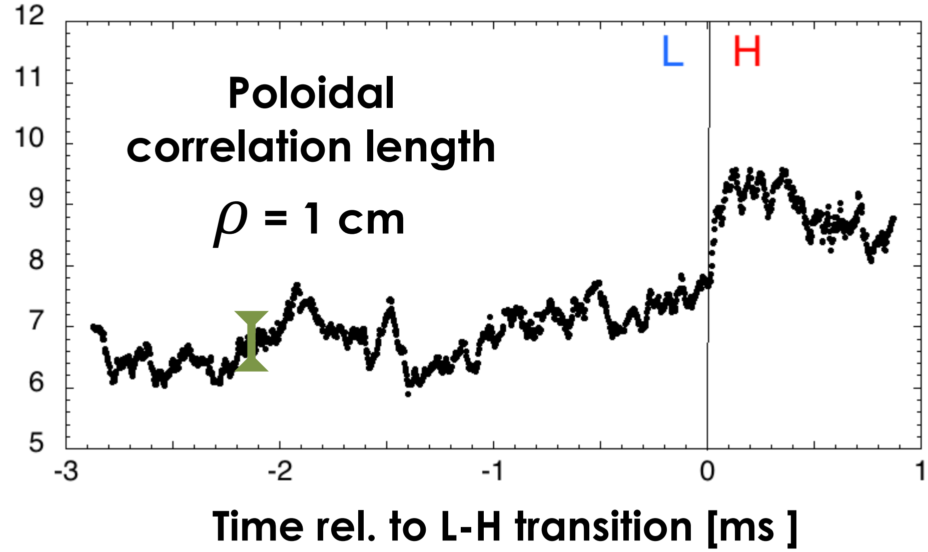
- Inboard reduction in the relative GPI light fluctuation level
- Outboard reduction of blob activity.

Is there a detectable trigger of the L-H transition?

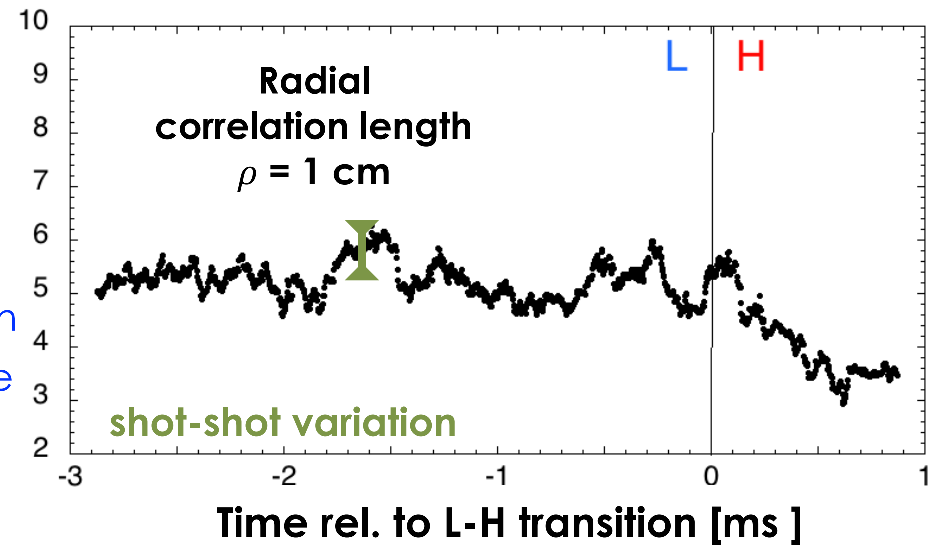
There is no significant change of turbulence quantities *preceding* the L-H transition but clear drop in fluctuation levels (~100 μs) across the L-H transition as expected

Averaged over all the 17 discharges





- **The turbulence quantities are averaged over multiple discharges (1cm inside LCFS)**
  - note zero suppressed in all plots.

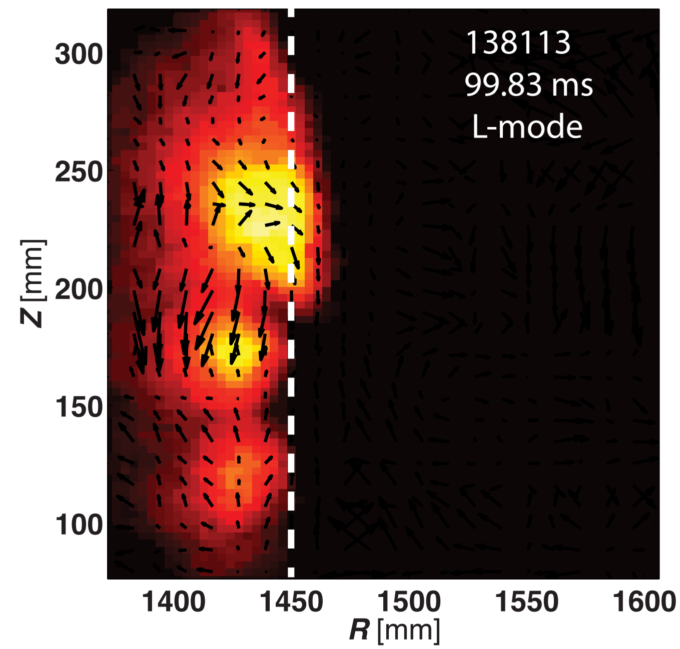


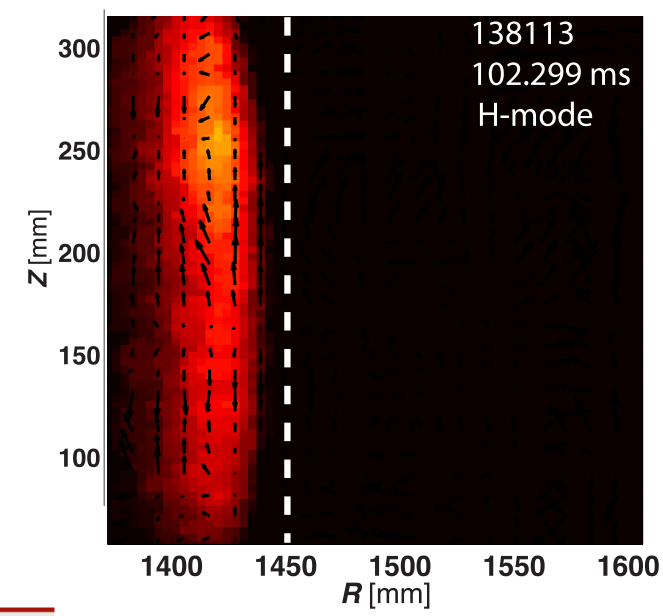
- **Across the L-H transitions:**
  - Slight increase in the average poloidal correlation length
  - Loss of radial correlation is translated in a slight decrease in the radial correlation length.

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**.
  - Comparison with TDE & Fourier type velocimetry shows ~80% correlation.
- Caveat:
  - Velocimetry techniques show only velocities **normal** to the intensity gradient.
  - This caveat is shared by **all** velocimetry approaches.





Approach for the decomposition of the velocity field components

- Reynolds decomposition should be applied to the whole flux surface.
- However, GPI view is limited to a 30 x 24 cm patch of the flux surface.
  - The flux-surface average is replaced by a temporal average.

- For each velocity component,

$$v_i = \bar{v}_i + \tilde{v}_i, \;\; i \in [r, \theta], \;\; \forall t$$

$$\text{High-pass filter of } v(r,\theta,t) \text{ at 1 kHz} \longrightarrow \tilde{v}(r,\theta,t)$$

$$\text{Low-pass filter of } v(r,\theta,t) \text{ at 1 kHz} \longrightarrow \bar{v}(r,\theta,t)$$

This cutoff frequency was chosen to include the poloidally oscillating flow (2 - 5 kHz) described in ref. Zweben et al. PoP (2010) into the non zonal component.

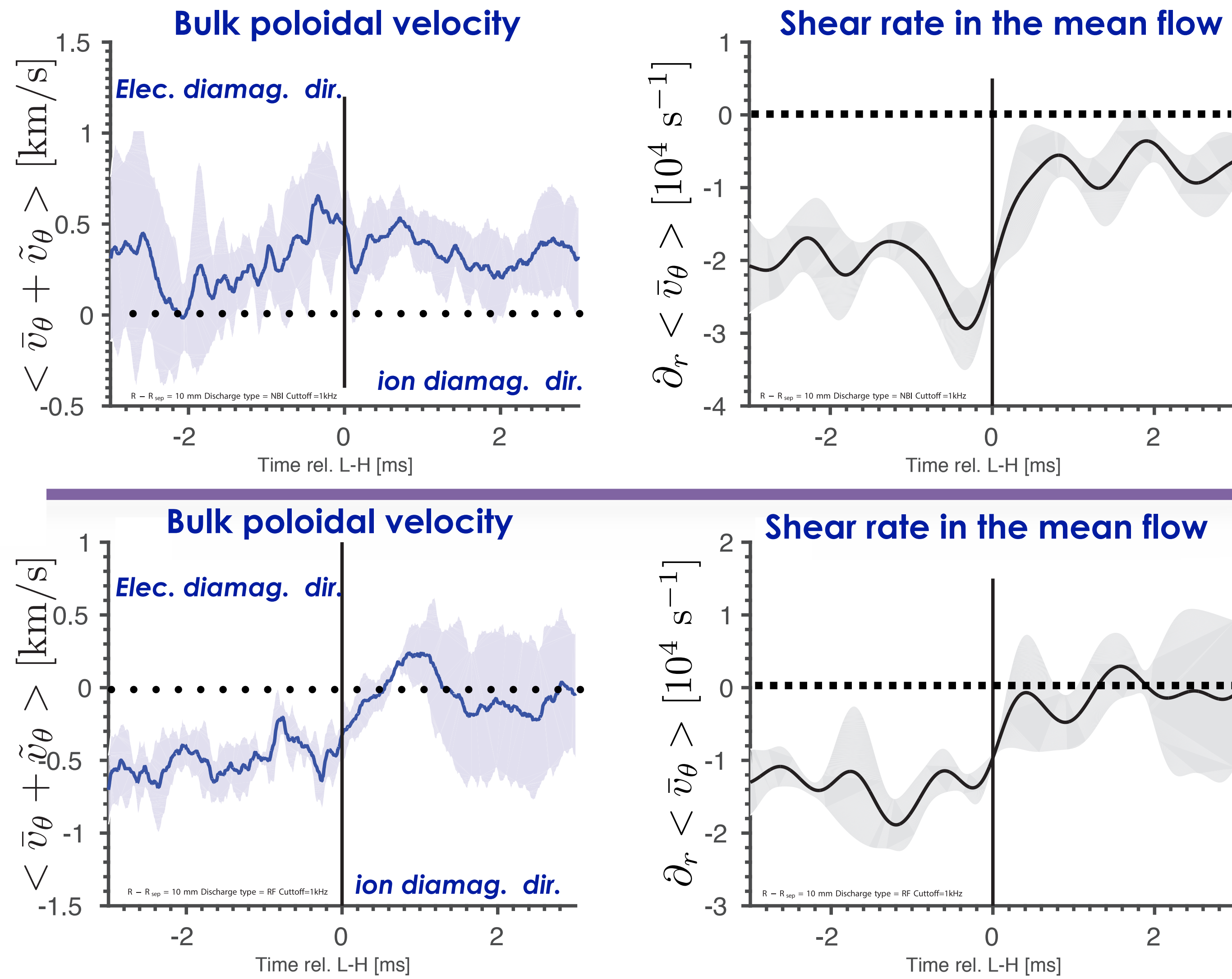
Variations (1 - 2 kHz) around this cutoff do not qualitatively change the results presented here.

The inferred absolute shear in the mean flow decreases across the L-H transition, which is inconsistent with the shear model

NBI

The shaded area represent the std over multiple discharges

RF



- **GPI emission bands become radially narrow across the L-H transition and the fluctuation level drops in H-mode: Decreasing shear flow in H-mode may be an artifact of the velocimetry.**

The analysis rest on this energy balance between flows and turbulence including the electron parallel dynamic

Stoltzfus-Dueck, PoP, **23** 054505 (2016)

(see next talk for discussion)

Turbulence fluctuations

Thermal free energy — **non-zonal ExB energy** — **Zonal ExB energy**

$$\partial_t \left(\frac{T_{e0}}{2n_{e0}} \tilde{n}_e^2 + \frac{n_0 m_i \left\langle \tilde{v}_E^2 \right\rangle}{2} + \frac{n_0 m_i \left\langle \bar{v}_E \right\rangle^2}{2} \right) = \text{sources} + \text{sinks}$$

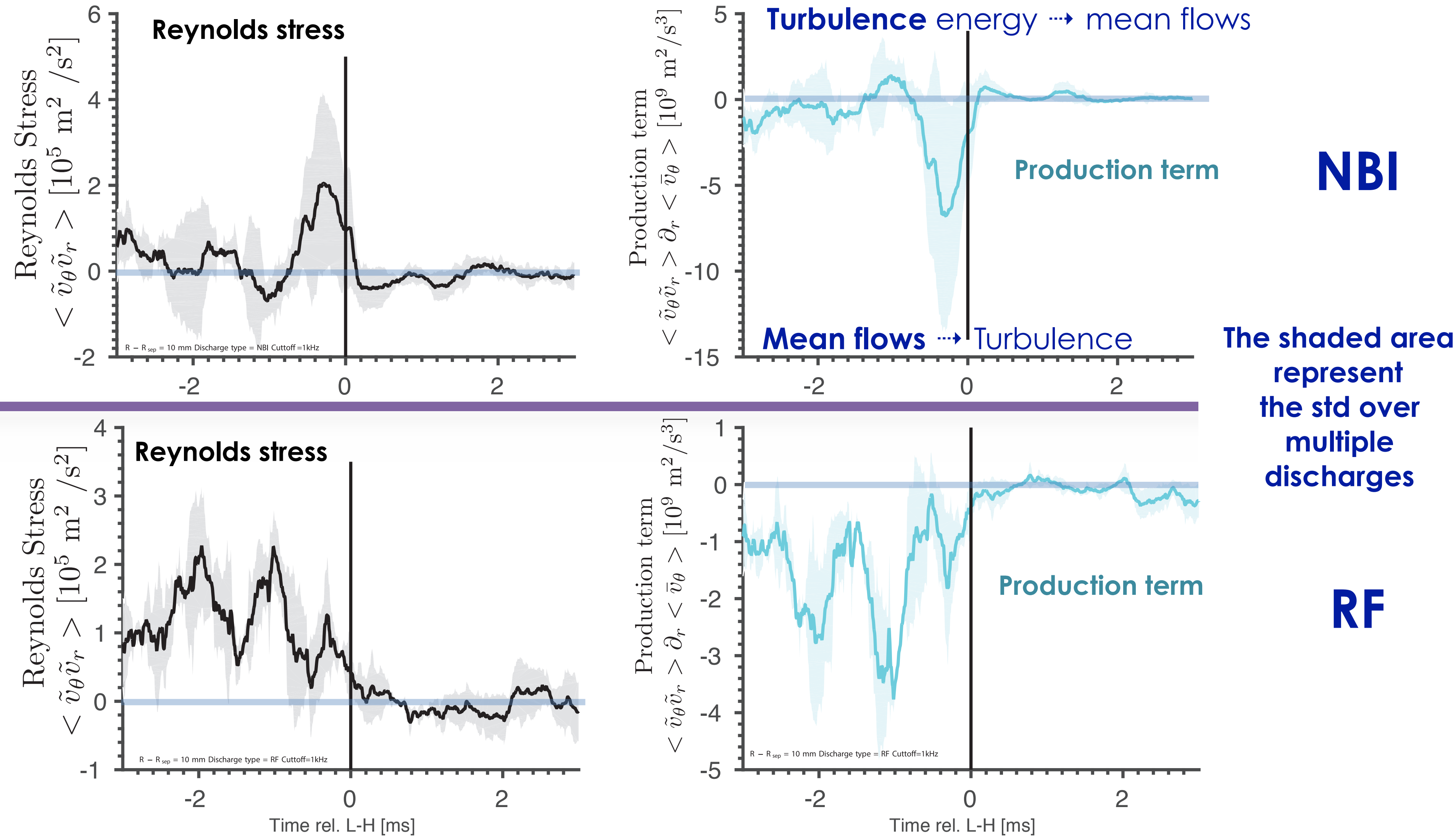
$$n_0 m_i \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle \partial_r \left\langle \bar{v}_\theta \right\rangle$$

Production term = P

$P > 0 \Rightarrow$ energy is transferred from **turbulence** to mean flows.

$P < 0 \Rightarrow$ energy is transferred from mean flows to **turbulence.**

For all heating schemes, we observe that the energy is transferred from mean flows to turbulence 1 cm inside the separatrix



- This is inconsistent with the turbulence depletion hypothesis prior to the L-H transition.
- Such negative production term has previously been observed in JET ohmic discharge.

Sanchez JNM **337** 296 (2005)

The analysis rest on this energy balance between flows and turbulence including the electron parallel dynamic

Stoltzfus-Dueck, PoP, **23** 054505 (2016)

Turbulence fluctuations

Thermal free energy | **non-zonal ExB energy** | **Zonal ExB energy**

$$\partial_t \left(\frac{T_{e0}}{2n_{e0}} \tilde{n}_e^2 + \frac{n_0 m_i \langle \tilde{v}_E^2 \rangle}{2} + \frac{n_0 m_i \langle \bar{v}_E \rangle^2}{2} \right) = \text{sources} + \text{sinks}$$

$E_{\tilde{n}}$

$$n_0 m_i \langle \tilde{v}_r \tilde{v}_\theta \rangle \partial_r \langle \bar{v}_\theta \rangle$$

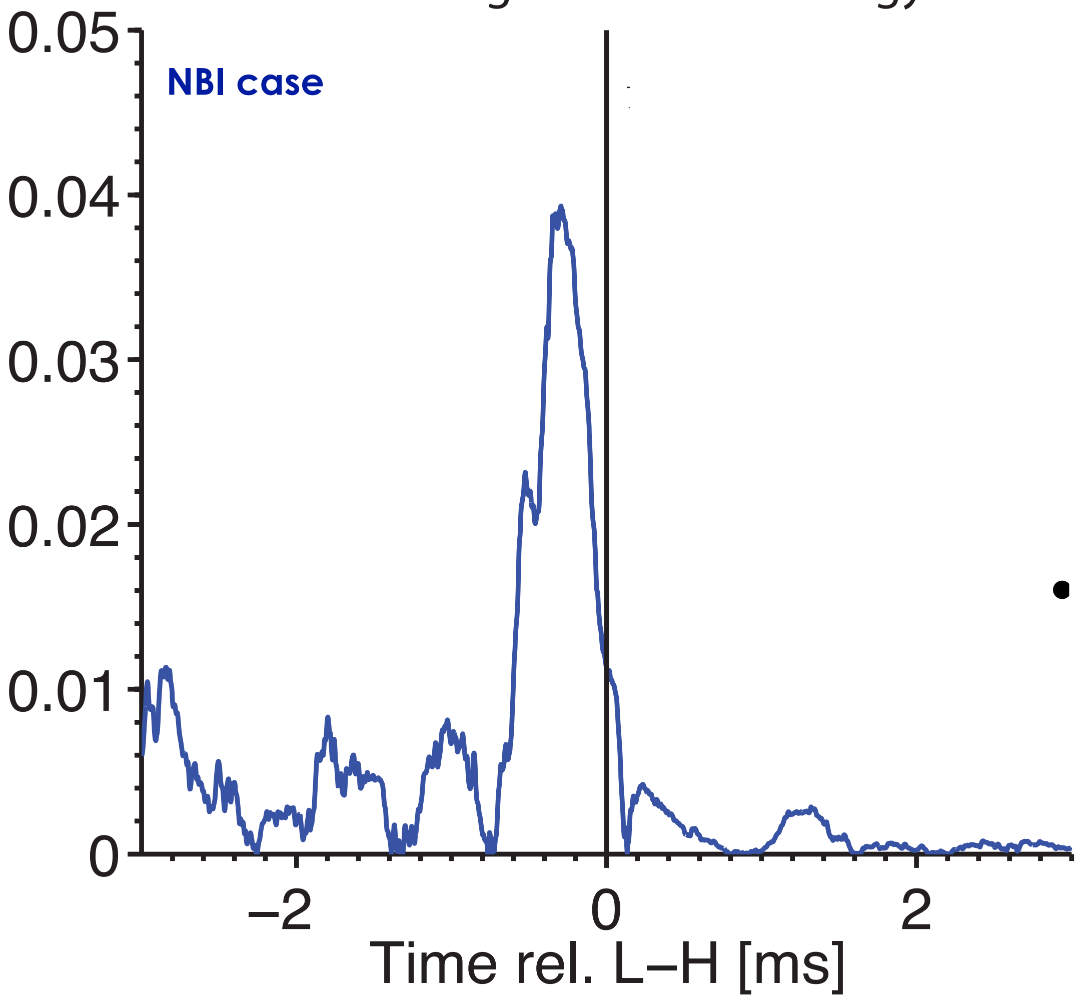
Production term = P

Change in thermal free energy during the L-H transition

$(\tau_{L-H}^{exp})^{-1} (E_{\tilde{n}}|_L - E_{\tilde{n}}|_H)$ & **P**

Even the absolute value production term cannot account for the L-H transition duration

Ratio of the Production term to the change in thermal energy



- We compare the change in the free energy into a thermal portion between the L and H mode phases to the production term

$$\frac{P}{P_0} \doteq \frac{n_0 m_i (\tilde{v}_E^x \tilde{v}_E^y)\partial_x \left\langle v_E^y \right\rangle}{(\tau_{L-H}^{exp})^{-1}(E_{\tilde{n}}|_L - E_{\tilde{n}}|_H)}$$

- Using the computed production term, the L-H transition duration yields 25 ms much slower than our observation.
  - Note the results are qualitatively similar for RF and Ohmic cases (not shown here)

Energy balance between flows and turbulence including the electron parallel dynamic

STOLTZFUS-DUECK, PoP **23** 054505 (2016)

Electron parallel conduction fast timescale

$$j_{||}\nabla_{||}\varphi$$

Thermal free energy — **non-zonal ExB energy** — **Zonal ExB energy**

$$\partial_t\left(\frac{T_{e0}}{2n_{e0}}\tilde{n}_e^2+\frac{n_0 m_i\left\langle\tilde{v}_E^2\right\rangle}{2}+\frac{n_0 m_i\left\langle\bar{v}_E\right\rangle^2}{2}\right)=\text{sources}+\text{sinks}$$

slow time scale

Production term

$$n_0 m_i\left\langle\tilde{v}_r\tilde{v}_\theta\right\rangle\partial_r\left\langle\bar{v}_\theta\right\rangle$$

Moves as a single unit given the fast time scales $t\sim\frac{qR}{v_{the}}$

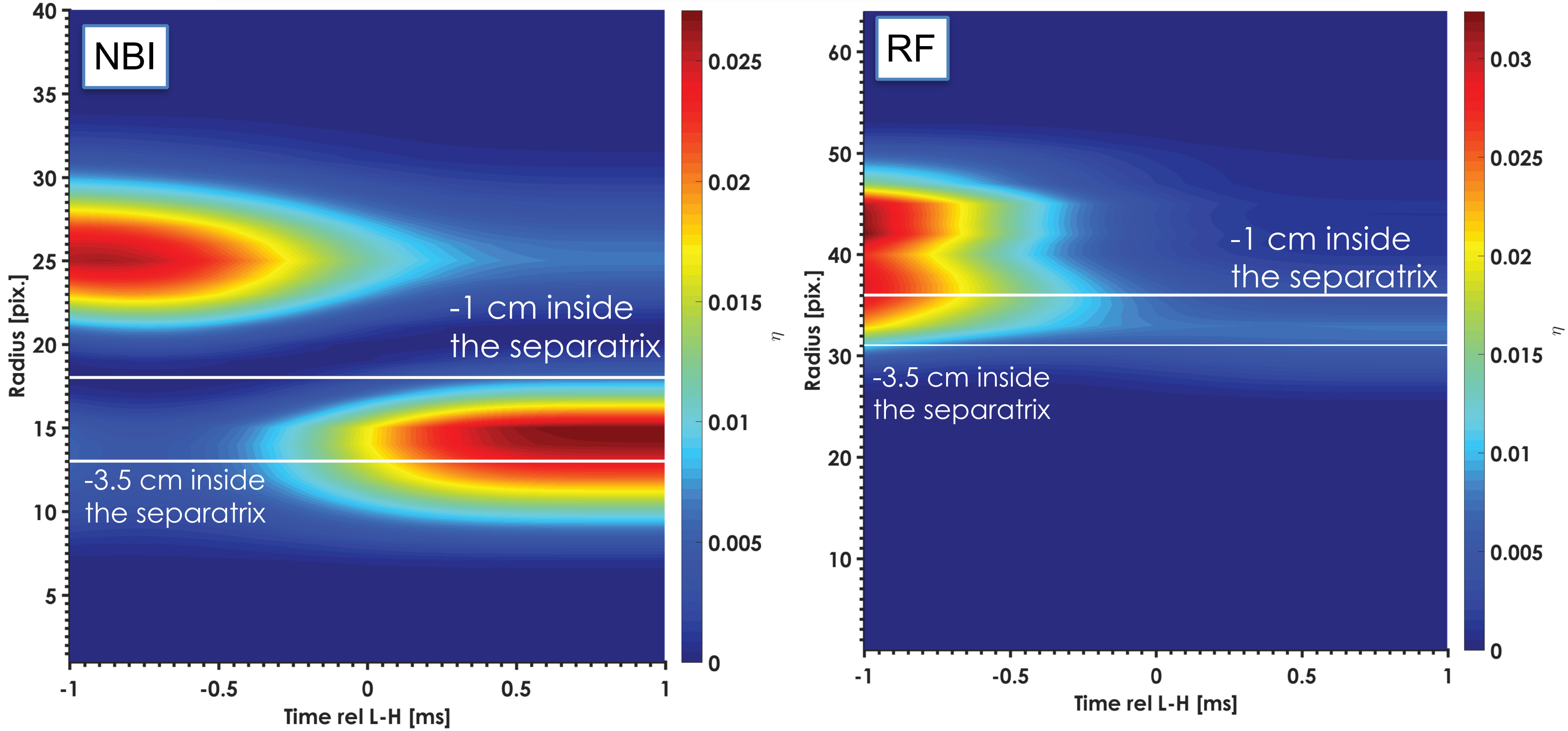
$$\left(\frac{T_{e0}}{2n_{e0}}\tilde{n}_e^2+\frac{n_0 m_i\left\langle\tilde{v}_E^2\right\rangle}{2}\right)$$

For energy transfer to mean flows to deplete the turbulence, we must have

$$\frac{\left\langle\bar{v}_\theta^2\right\rangle/c_s^2}{\left(\tilde{n}_e/n_{e0}\right)^2}\gtrsim 1$$

The kinetic energy in the mean flow is much smaller than the thermal free energy

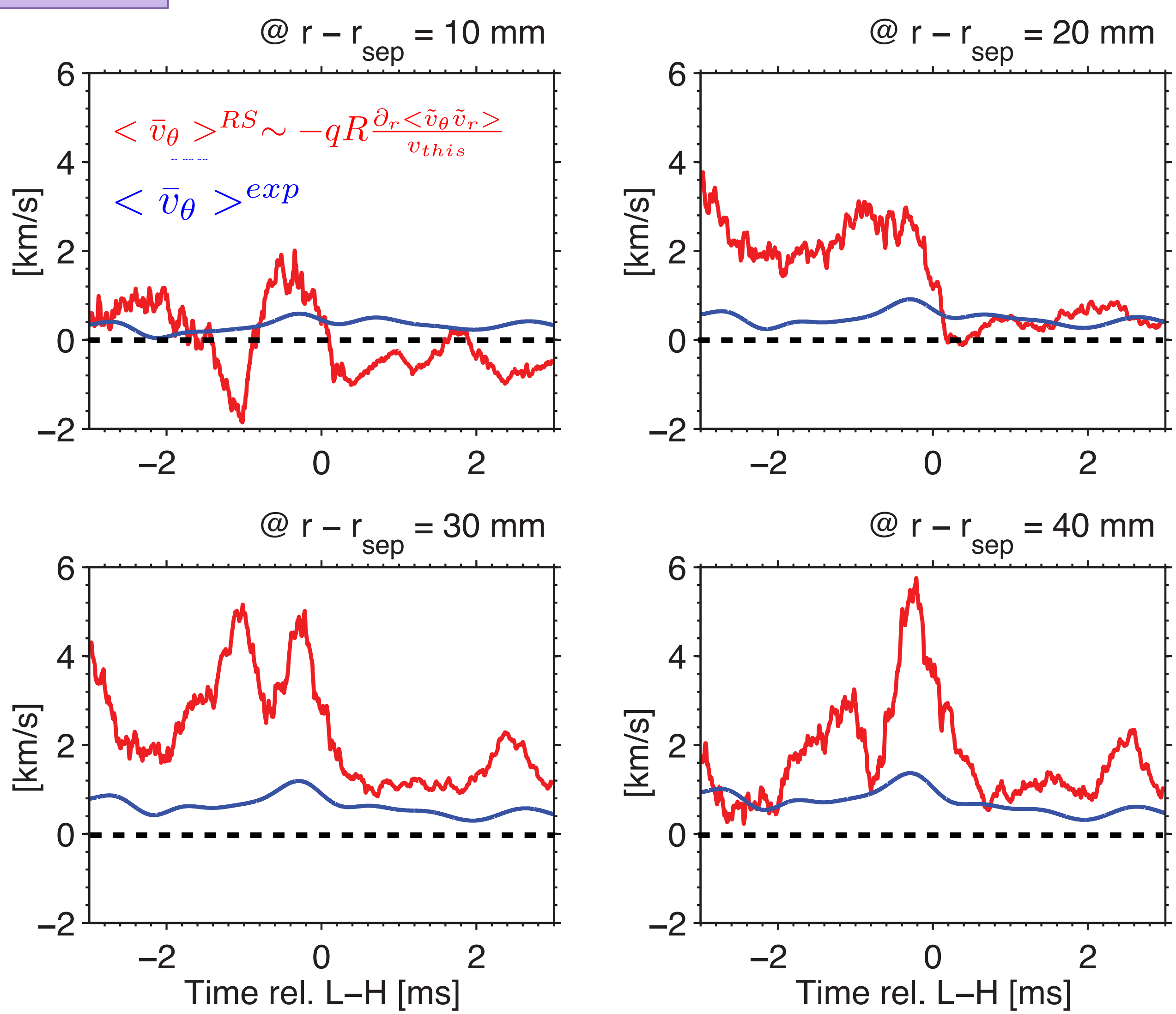
$$\eta \doteq \frac{\langle \bar{v}_\theta \rangle^2 / c_s^2}{(\tilde{n}_e / n_{e0})^2} \Longrightarrow \frac{\langle \bar{v}_\theta \rangle^2 / c_s^2}{\left(<\tilde{I}^2>_{[L]} / \bar{I}^2 \right)}$$



- The radial structure is not yet understood.

Contribution of the Reynolds stress to the mean flow cannot necessarily be discarded

NBI case



- Crude estimate the Reynolds stress-driven flow

- **Reynolds stress-driven mean flow and the measured mean flow are of the same order of magnitude**
  - **consistent to results in Refs.**

Hildalgo et al., PPCF, **42**, A153, (2000)
McKee et al., NF **49**, 115016 (2009)
Manz et al., Phys. Plasmas, **19**, 072311, (2012).

Results in previous experimental investigations motivated the examination of the energy exchange dynamics on NSTX

- We consider the following energy balance to evaluate the turbulence depletion:
  - Most experimental results neglected the thermal free energy

Thermal free energy | non-zonal ExB | Zonal ExB

$$\partial_t \left(\frac{T_{e0}}{2n_{e0}} \tilde{n}_e^2 + \frac{n_0 m_i \left\langle \tilde{v}_E^2 \right\rangle}{2} + \frac{n_0 m_i \langle \bar{v}_E \rangle^2}{2} \right) = \text{sources} + \text{sinks}$$

- We evaluated this energy transfer dynamics and possible links with the L-H transition on NSTX edge using the gas-puff-imaging for three heating schemes (**NBI**, **RF**, and *Ohmic*)
  - The edge turbulence using GPI showed no consistent changes preceding the L-H
  - These turbulence quantities change from before and after the transition but this does not help to identify the L-H transition mechanism.
  - Using a velocimetry approach ODP, we show that turbulence depletion is not necessarily mediated by the perpendicular Reynolds stress.
  - The turbulence energy transfer to mean flow is not key to the L-H transition, contrary to the predator- prey model.
  - Non negligible contribution to the poloidal flows by the Reynolds stress, however, is plausible.

Future work will attempt to better quantify the uncertainties in 2D velocimetry in H-mode by making quantitative comparison with turbulence simulations.

Supplementary material

Energy balance between flows and turbulence including the electron parallel dynamic

STOLTZFUS-DUECK, PoP **23** 054505 (2016)

Electron parallel conduction

$j_{||}\nabla_{||}\varphi$

fast time scale $t \sim \frac{qR}{v_{the}}$ → $\frac{e\tilde{\varphi}}{T_{e0}} \sim \frac{\tilde{n}_e}{n_{e0}}$ leads to → $\frac{\langle \tilde{v}_\theta^2 \rangle / c_s^2}{(\tilde{n}_e/n_{e0})^2} \sim k_\perp^2 \rho_s^2 \ll 1$

Thermal free energy — non-zonal ExB energy — Zonal ExB energy

$$\partial_t \left(\frac{T_{e0}}{2n_{e0}} \tilde{n}_e^2 + \frac{n_0 m_i \langle \tilde{v}_E^2 \rangle}{2} + \frac{n_0 m_i \langle \bar{v}_E \rangle^2}{2} \right) = \text{sources} + \text{sinks}$$

slow time scale

Production term

$$n_0 m_i \langle \tilde{v}_r \tilde{v}_\theta \rangle \partial_r \langle \bar{v}_\theta \rangle$$

Moves as a single unit given the fast time scales $t \sim \frac{qR}{v_{the}}$

$$\left(\frac{T_{e0}}{2n_{e0}} \tilde{n}_e^2 + \frac{n_0 m_i \langle \tilde{v}_E^2 \rangle}{2} \right)$$

For energy transfer to mean flows to deplete the turbulence, we must have

$$\frac{\langle \bar{v}_\theta^2 \rangle / c_s^2}{(\tilde{n}_e/n_{e0})^2} \gtrsim 1$$

Some experimental investigations are in agreement with the direct turbulence depletion to mean flow

- 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:
  - First peaking o the normalized Reynolds power
  - Then the collapse of the turbulence
  - Finally the rise of the diamagnetic electric field shear

Cziegler et al. PPCF 2014

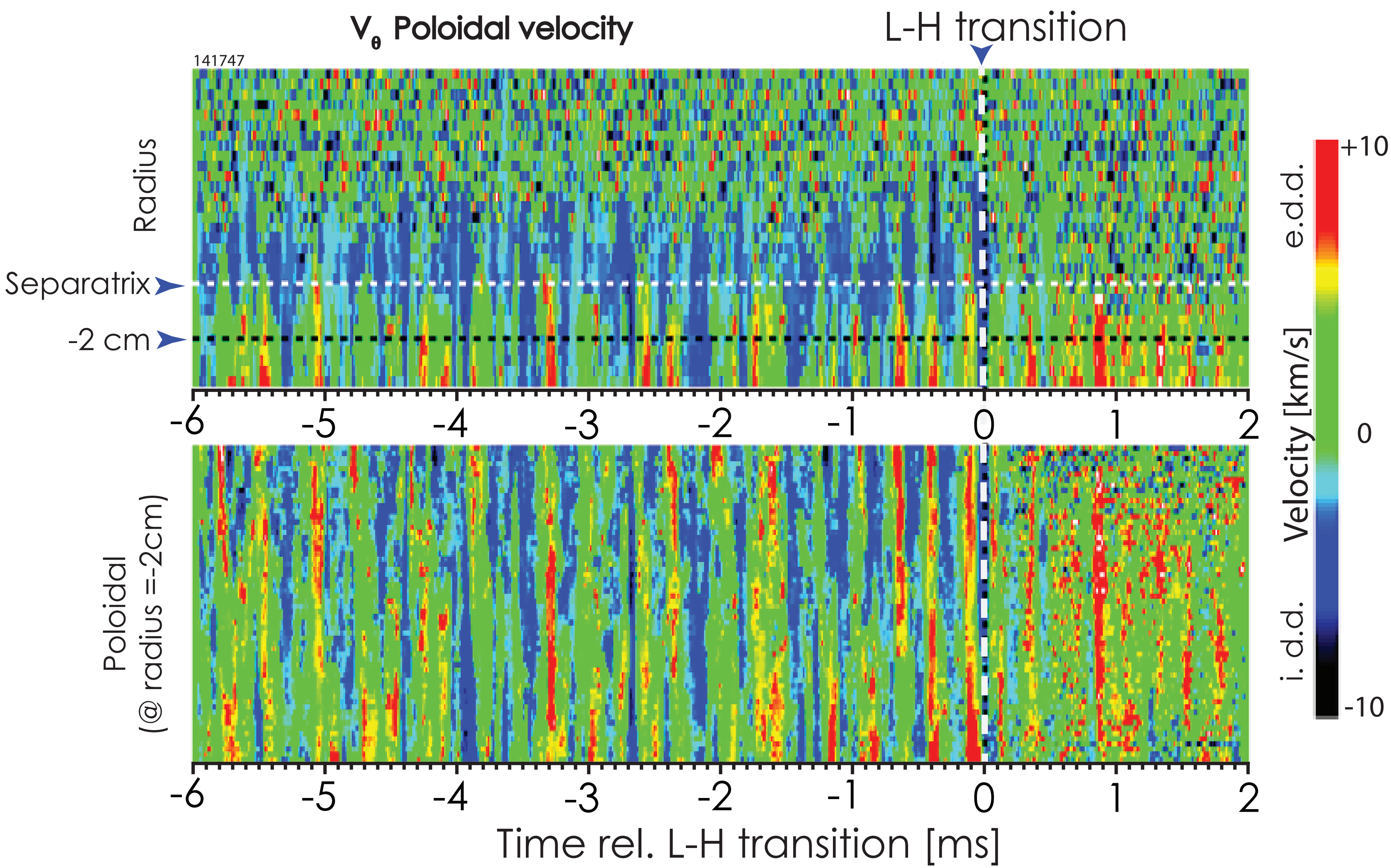
- On DIII-D, Increasing heating power increases the energy transfer from turbulence to the poloidal flow, and the edge flow shearing rate that then exceeds the decorrelation rate, suppressing turbulence and triggering the transition.

Yan et al. PRL 2014

- In JET, near the edge shear layer, no evidence of energy transfer from turbulence to flows.

Sanchez et al. JNM 2005

Poloidal flow



The kinetic energy in the mean flow remains smaller than the thermal free energy at two radii (1 cm & 3.5 cm) inside the LCFS