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NSTX-U

Energy Exchange Dynamics across L-H Transitions in NSTX

A. Diallo, S. Banerjee*, S.J. Zweben, T. Stoltzfus-Dueck
Princeton Plasma Physics Laboratory, Princeton NJ 08540 USA.
*Institute for Plasma Research, Gandhinagar, Gujarat, India.

PPPL

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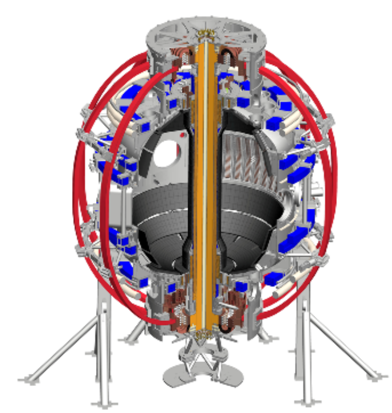
EX/5-3



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L-H transition is defined as …

- It is the sudden transition to a state of good energy confinement in the edge:
  - Expected mode of operation for ITER.

Wagner PRL (1982)

- It appears as heating power increases past some threshold.

What is the mechanism driving the L-H transition?

Most models on L-H transition have two parts

1. **Generation of sheared flow.**

2. **Suppression of turbulence by flow shear.** **[Focus of this Talk]**

L-H transition theories are summarized
Connor and Wilson PPCF 42 R1 (2000) Review paper.

Two main mechanisms can occur for turbulence suppression by flow shear

1. Energy transfer to flows *directly* depletes the turbulent fluctuations.

non-zonal ExB energy → Zonal ExB energy

$$\frac{n_0 m_i \left\langle \tilde{v}_\perp^2 \right\rangle}{2} \longrightarrow \frac{n_o m_i \langle \bar{v}_\theta \rangle^2}{2}$$

NSTX L-H transition CANNOT be explained by the depletion of turbulence due to energy transfer to zonal flows

2. Flow shear depletes the turbulence in other ways

NSTX data does not rule out such mechanisms.

Some experimental investigations showed a transfer of energy from turbulence to mean flow

- [x] 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
  Xu et al. NF 54 (2014)

- [x] Recent work on C-Mod using gas-puff imaging (GPI) provided a timeline for the L-H transition:

  Cziegler et al. PPCF 2014

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

- [x] On DIII-D, heating power increases the energy transfer from turbulence to the poloidal flow.

  Yan et al. PRL 2014

  See Review paper Tynan PPCF 2016

- [ ] However, in JET, near the edge shear layer, no evidence of energy transfer from turbulence to flows was found.

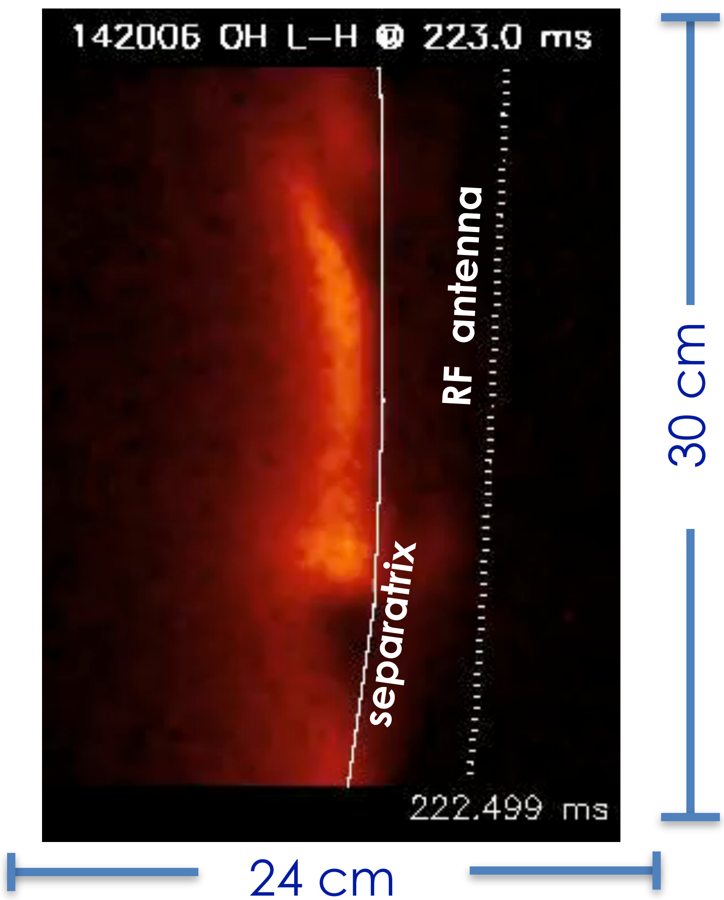
  Sanchez et al. JNM 2005

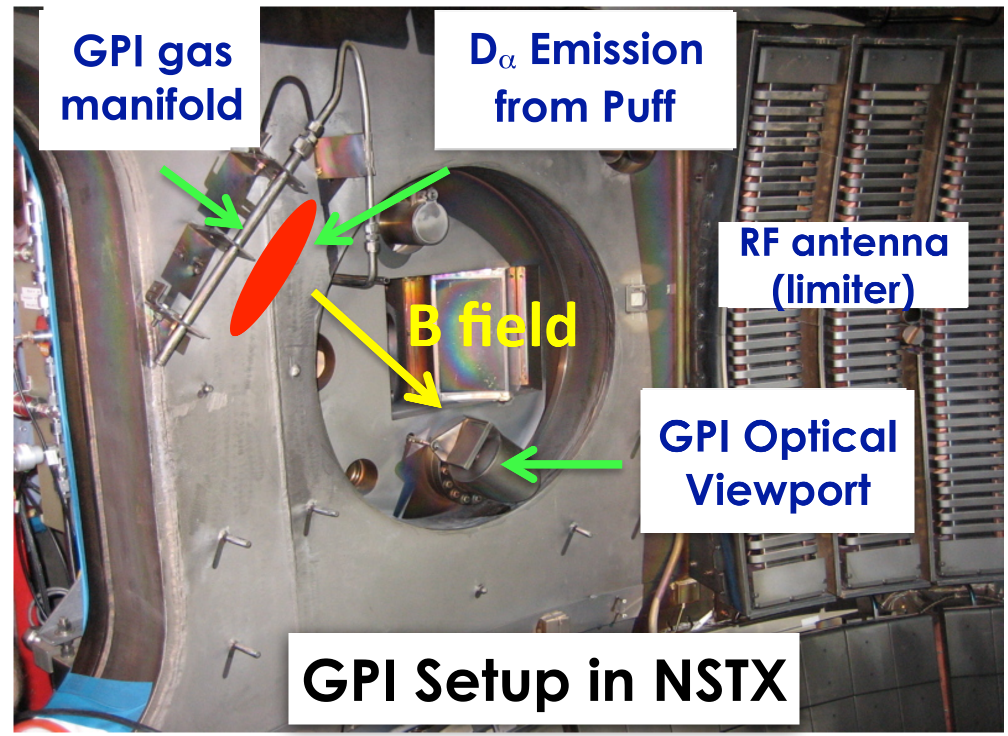
NSTX results are inconsistent with energy transfer to flows directly depletes the turbulent fluctuations.

Gas-puff imaging diagnostic is central to the NSTX L-H transitions analysis

Zweben PoP (2010) for detailed description

- GPI provides edge turbulence images
  - **Temporal resolution ~ 2.5 μs**
  - **Spatial resolution ~ 1 cm**





Discharge characteristics (total of 17):

NBI-Heated: 138113:138119

Ohmically-Heated: 141745:141751 (not shown here)

RF- Heated: 141919:141922, 142006 (not shown here)

Gas-puff imaging diagnostic is central to the NSTX L-H transitions analysis

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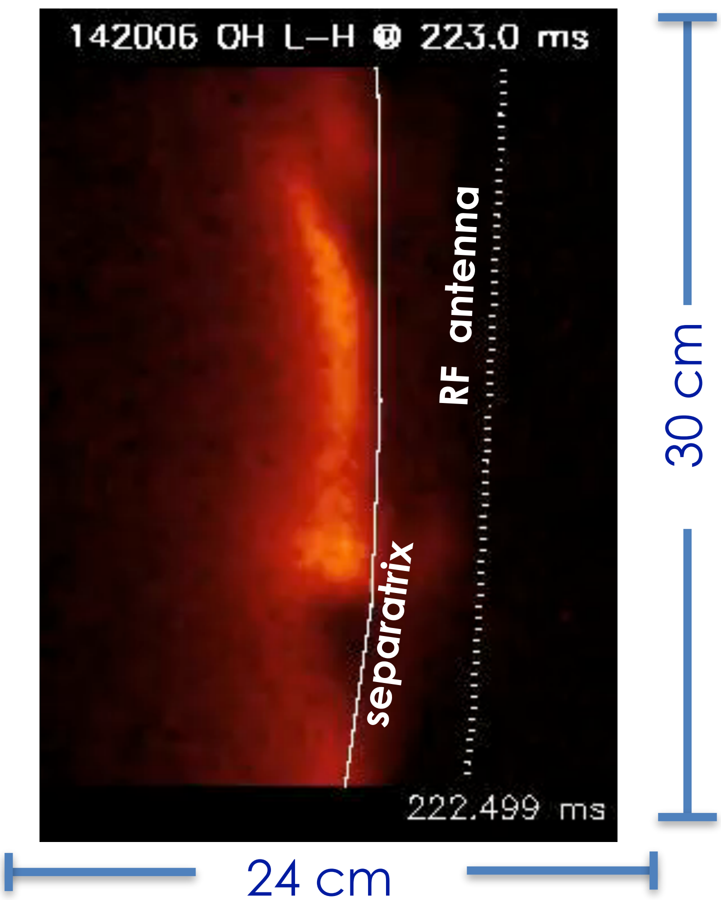
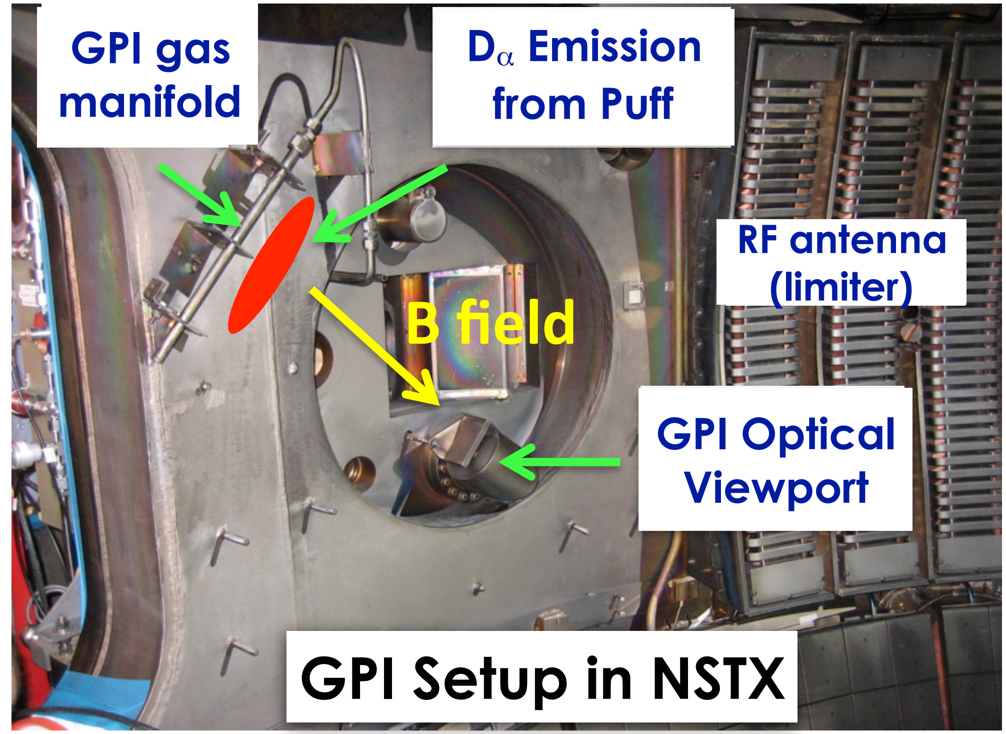




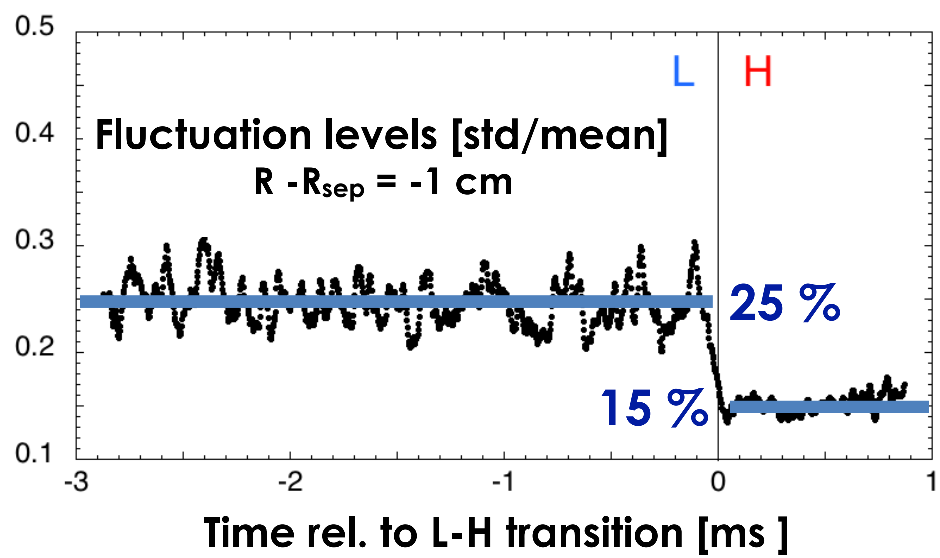
Discharge characteristics (total of 17):

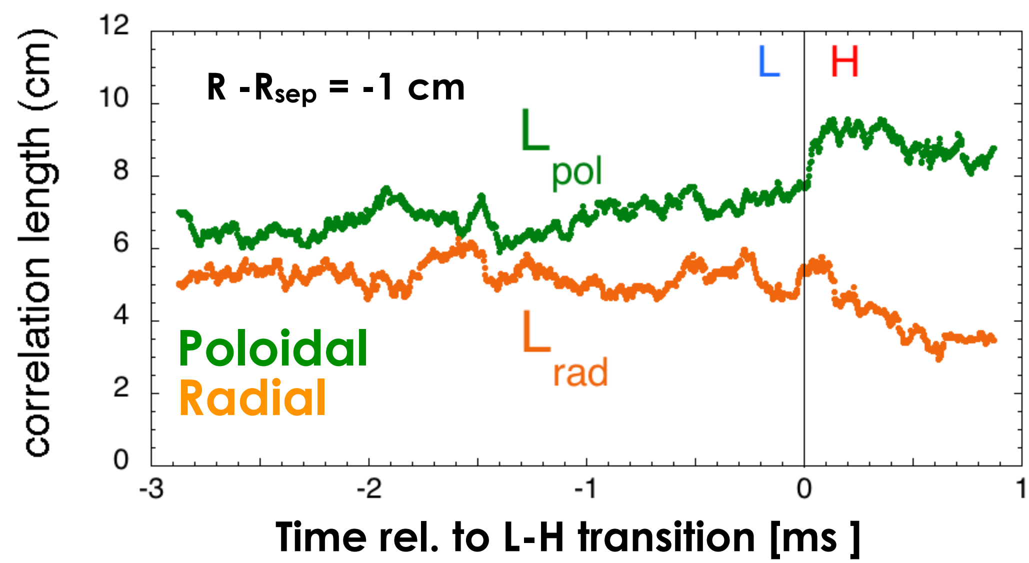
NBI-Heated: 138113:138119

Ohmically-Heated: 141745:141751 (not shown here)

RF- Heated: 141919:141922, 142006 (not shown here)

There is no significant change of turbulence quantities *preceding* the L-H transition but clear drop in fluctuation levels across the transition





- The turbulence quantities are averaged over multiple discharges.
- Turbulence quantities changes are similar to previous observations.

What causes the drop in fluctuation levels across the L-H transition?

Can direct energy transfer from turbulence to mean flow explain this?

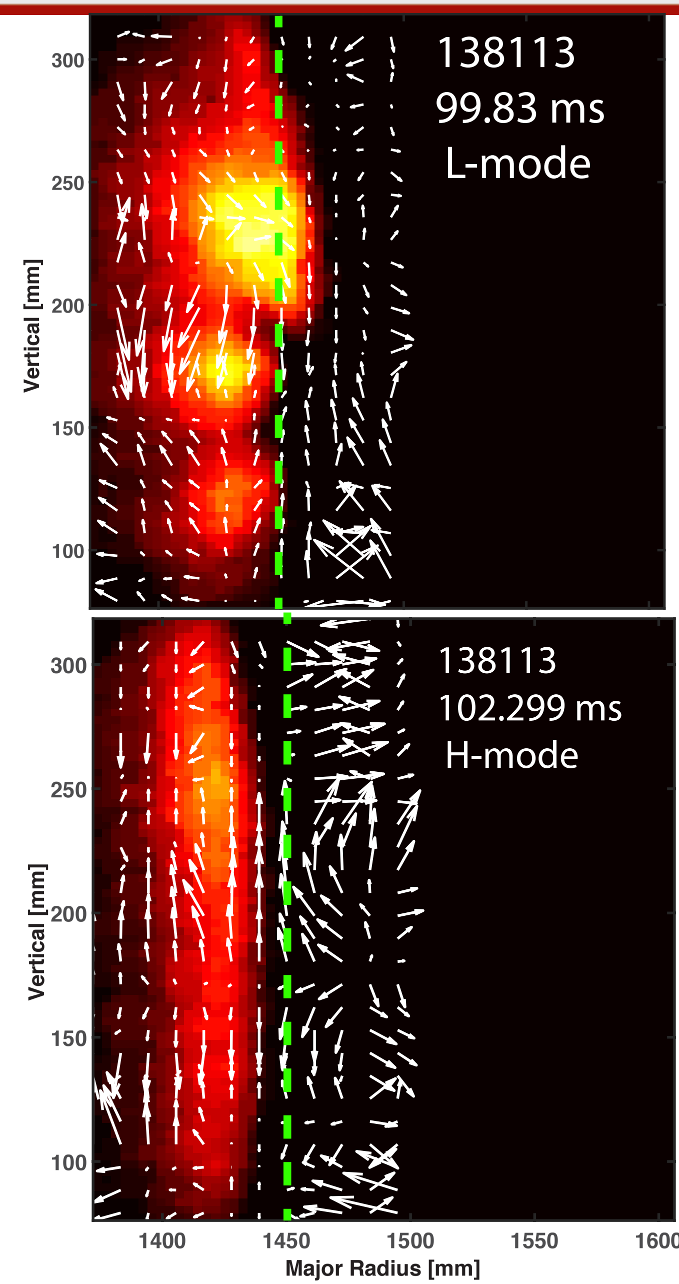
Orthogonal dynamic programming (ODP) applied to GPI data for imaging velocimetry

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

- ODP enables to reconstruct a **2D velocity field**.
  - Comparison with TDE & Fourier type velocimetry shows ~80% correlation.
- For each velocity component,

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

- Caveat:
  - Velocimetry techniques show only velocities **normal** to the intensity iso-contours.
  - This caveat is shared by **all** velocimetry approaches.



We test the suppression of turbulence via energy transfer from turbulence to mean flow

- Evaluate the sign of production term: does turbulence drive flows or vice versa?

- Is the absolute value of the production term big enough to explain the rate of change of the thermal free energy?

- Does the energy in the mean flow increase as much as the turbulence energy drops?

Energy transfer direction is determined using the production term

Positive Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

non-zonal ExB energy

$$\frac{n_o m_i \left\langle \tilde{v}_\theta^2 \right\rangle}{2}$$

P>0 →

← P<0

Zonal ExB energy

$$\frac{n_o m_i \left\langle \bar{v}_\theta \right\rangle^2}{2}$$

Negative Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

- **In order to deplete the turbulence the production term must be positive.**

In NSTX, energy is transferred from mean flows to turbulence

non-zonal ExB energy

$$\frac{n_o m_i \left\langle \tilde{v}_\theta^2 \right\rangle}{2}$$

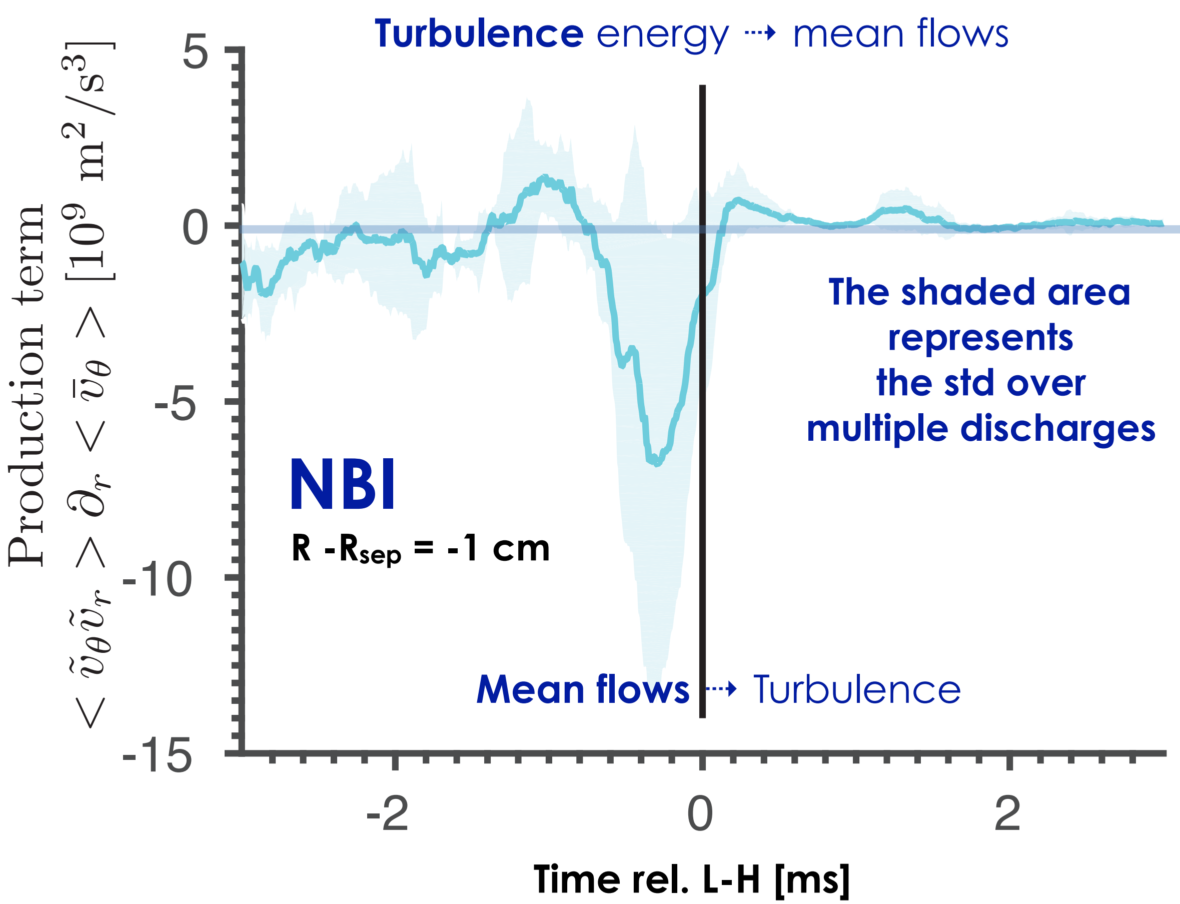
Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

Zonal ExB energy

$$\frac{n_o m_i \left\langle \bar{v}_\theta \right\rangle^2}{2}$$

Production term



- We observe energy transfer from zonal flow to turbulence.
- Inconsistent with the turbulence depletion hypothesis prior to the L-H transition.
- Explore additional terms in the energy balance equation.

We test the suppression of turbulence via energy transfer from turbulence to mean flow

- Evaluate the sign of production term: does turbulence drive flows or vice versa?

  In NSTX, energy is transferred from mean flows to turbulence

We test the suppression of turbulence via energy transfer from turbulence to mean flow

- Evaluate the sign of production term: does turbulence drive flows or vice versa?

  In NSTX, energy is transferred from mean flows to turbulence

- **Is the absolute value of the production term big enough to explain the rate of change of the thermal free energy?**

Recall: This energy balance between flow and turbulence

non-zonal ExB energy

$$\frac{n_o m_i \left\langle \tilde{v}_\theta^2 \right\rangle}{2}$$

Zonal ExB energy

$$\frac{n_o m_i \left\langle \bar{v}_\theta \right\rangle^2}{2}$$

Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

Thermal free energy is an additional reservoir for the turbulence energy

See paper for details
Stoltzfus-Dueck, PoP ***23*** *054505 (2016)*

Turbulence energy (E_{Turb})

Thermal free energy

$$\frac{n_{e0}T_{e0}}{2}\left(\frac{\tilde{n}_e}{n_{0e}}\right)^2$$

+

non-zonal ExB energy

$$\frac{n_o m_i \left\langle \tilde{v}_\theta^2 \right\rangle}{2}$$

Zonal ExB energy

$$\frac{n_o m_i \left\langle \bar{v}_\theta \right\rangle^2}{2}$$

Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

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non-zonal ExB energy

$$\frac{n_o m_i \left\langle \tilde{v}_\theta^2 \right\rangle}{2}$$

↔

Zonal ExB energy

$$\frac{n_o m_i \left\langle \bar{v}_\theta \right\rangle^2}{2}$$

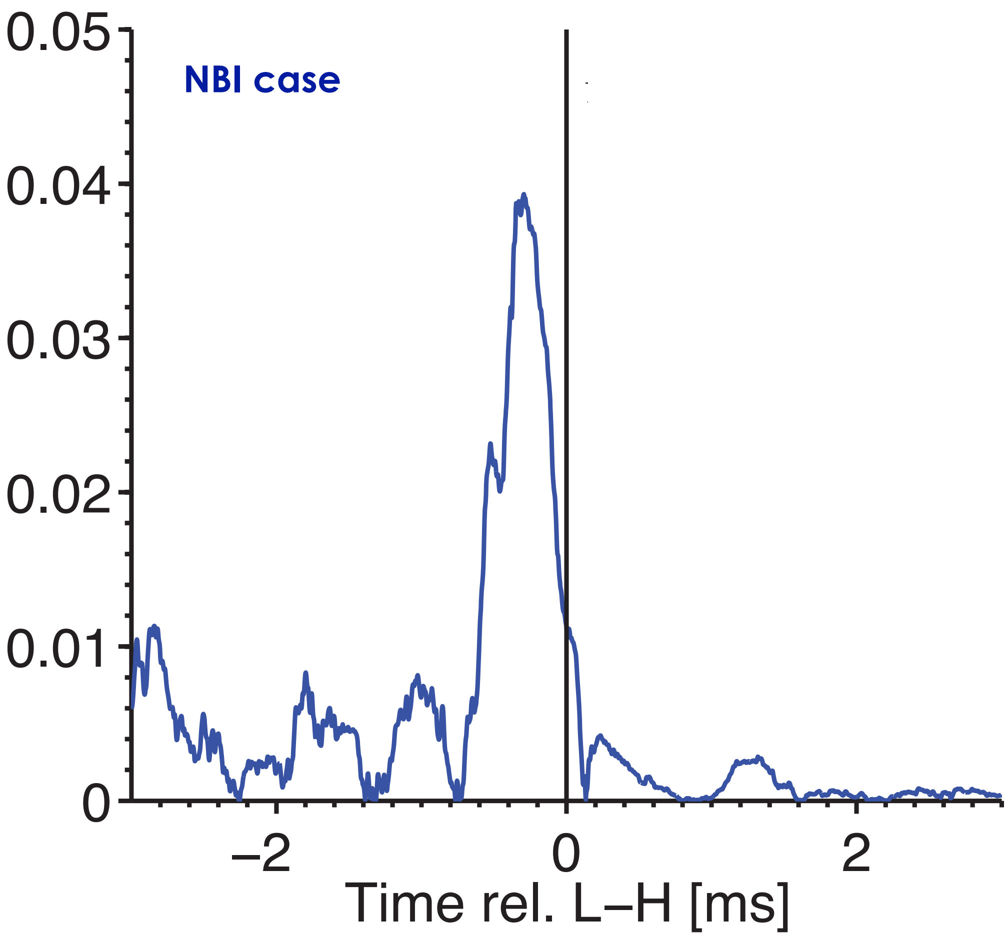
Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

Compare the rate of change of the thermal free energy over the L-H transition to the absolute value of the production term

Production term is much less than the observed rate of change of the thermal free energy

$$\frac{P}{P_0} = \frac{|n_o m_i \langle \tilde{v}_\theta \tilde{v}_r \rangle \partial_r \langle \bar{v}_\theta \rangle|}{(E_{turb}|_L - E_{turb}|_H)\tau_{L\rightarrow H}^{-1}}$$



- Ratio NEEDS to be around 1 to have turbulence suppression.
- Ratio is much less than 1 so inconsistent with the turbulence depletion.

Results are qualitatively similar for RF and Ohmic cases.

We test the suppression of turbulence via energy transfer from turbulence to mean flow

- Is the absolute value of the production term big enough to explain the rate of change of the thermal free energy?

Production term is much less than the observed rate of change of the thermal free energy

We test the suppression of turbulence via energy transfer from turbulence to mean flow

- Is the absolute value of the production term big enough to explain the rate of change of the thermal free energy?

Production term is much less than the observed rate of change of the thermal free energy

- Does the energy in the mean flow increase as much as the turbulence energy drops?

Does the zonal flow absorb a significant fraction of the total turbulence energy?

Stoltzfus-Dueck, PoP 23 054505 (2016)

Turbulence fluctuation energies

Thermal free energy

non-zonal ExB energy

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

Zonal ExB energy

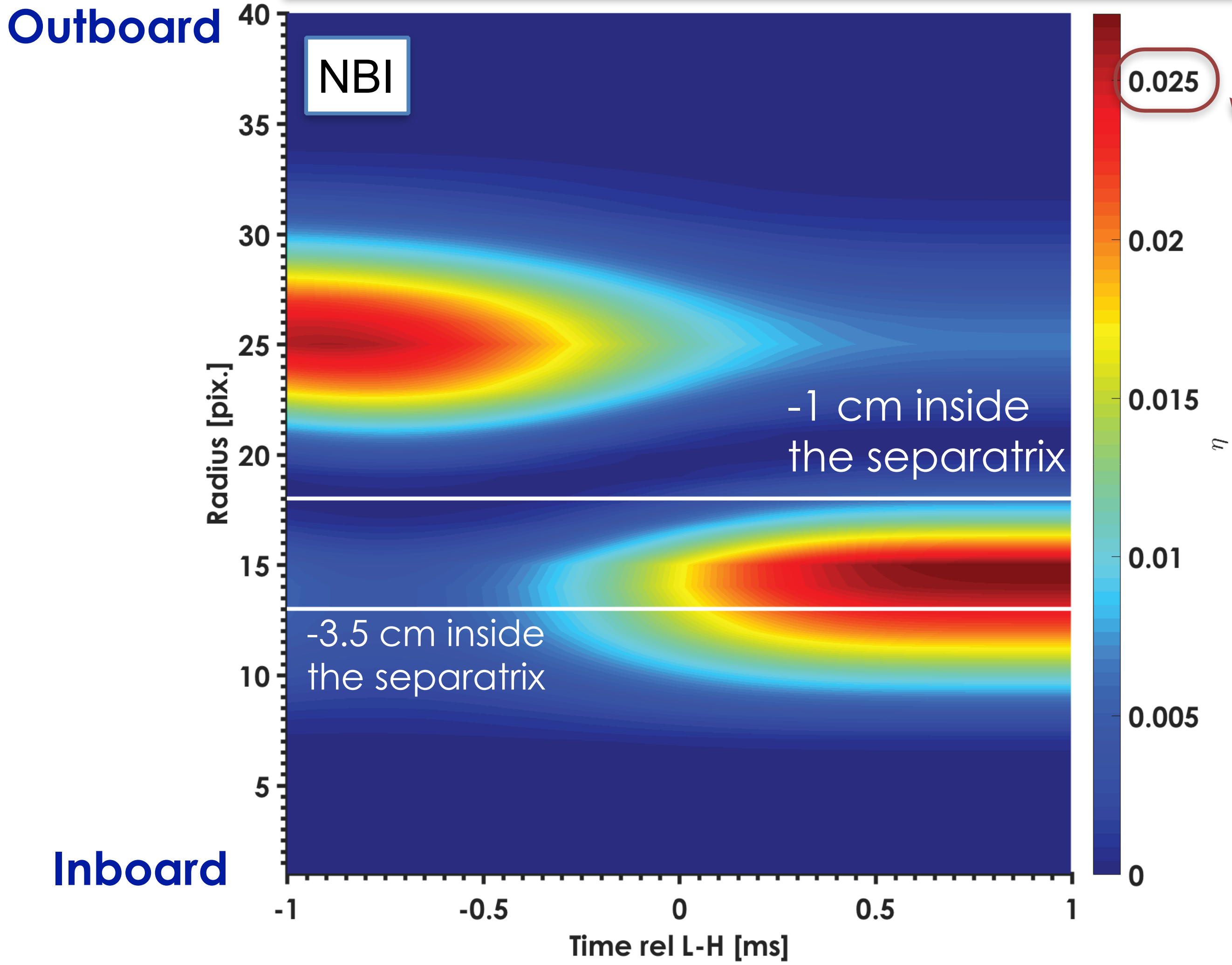
$$\frac{n_o m_i \left\langle \bar{v}_\theta \right\rangle^2}{2}$$

For zonal flows to take most of the turbulence energy:

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

Kinetic energy in the mean flow is always much smaller than the L-mode thermal free energy

$$\eta \doteq \frac{\langle \bar{v}_\theta \rangle^2 / c_s^2}{(\tilde{n}_e / n_{e0})^2_{\text{L-mode}}}$$



$$\eta \ll 1$$

Too weak to explain the rapid turbulence suppression at the L-H transition.

NSTX results do not support that energy transfer to flows directly depletes the turbulent fluctuations

- **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 energy:

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

Zonal ExB energy

Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

- **The turbulence quantities change across at the L-H transition but not *before*, so the changes do not help identify the L-H mechanism.**

- **Energy-transfer mechanism appears much too weak to explain the rapid turbulence suppression at the L-H transition.**
  - Uncertainties in 2D velocimetry may be order unity, but the energy transfer mechanism is ~100x too small to explain the turbulence suppression.
  - Future work will attempt to quantify the uncertainties in 2D velocimetry.

Supplementary material

Thermal free energy is an additional reservoir for the turbulence energy

See paper for details
Stoltzfus-Dueck, PoP ***23*** *054505 (2016)*

Turbulence energy (E_{Turb})

Thermal free energy

$$\frac{T_{e0}}{2n_{e0}}\tilde{n}_e^2$$

fast → Electron parallel conduction

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

non-zonal ExB energy

$$\frac{n_0 m_i \left\langle \tilde{v}_E^2 \right\rangle}{2}$$

slow ↔ Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

Zonal ExB energy

$$\frac{n_0 m_i \langle \bar{v}_E \rangle^2}{2}$$

Compare the change in power of the thermal free between L and H to the absolute value of the production term.

NSTX results do not support that energy transfer to flows directly depletes the turbulent fluctuations

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

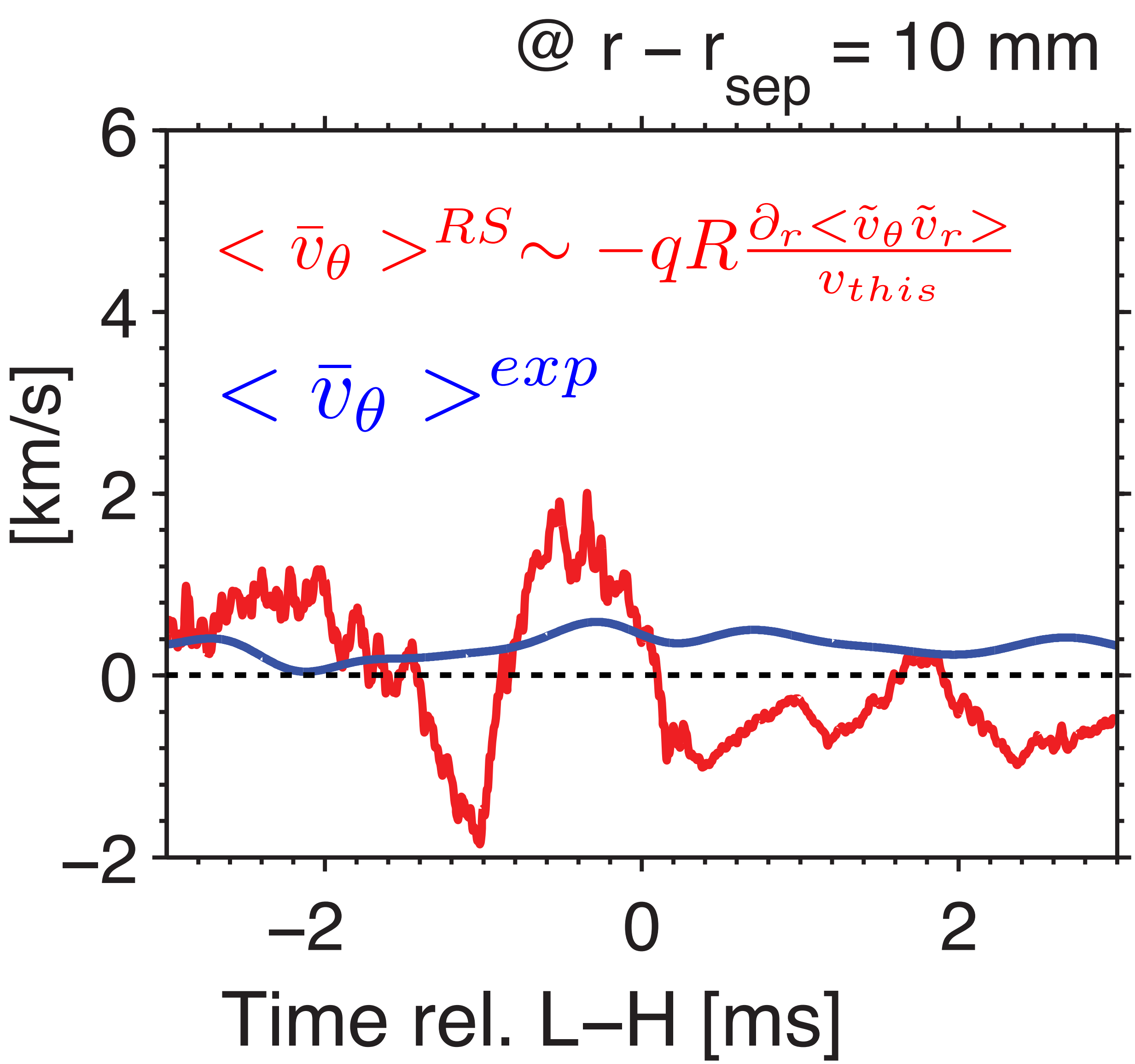
Thermal free energy $\frac{T_{e0}}{2n_{e0}}\tilde{n}_e^2$ ⟷ (**fast**; Electron parallel conduction $j_{||}\nabla_{||}\varphi$) ⟷ **non-zonal ExB energy** $\frac{n_0 m_i \langle \tilde{v}_E^2 \rangle}{2}$ ⟷ (**slow**; Production term $n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$) ⟷ **Zonal ExB energy** $\frac{n_0 m_i \langle \bar{v}_E \rangle^2}{2}$

- **The turbulence quantities change across at the L-H transition but not *before*, so the changes do not help identify the L-H mechanism.**

- **Energy-transfer mechanism is likely to be much too weak to explain the rapid turbulence suppression at the L-H transition.**

- **But, Reynolds stress may contribute significantly to the measured mean flows.**

Reynolds stress-driven mean flow and the measured mean flow are of the same order of magnitude



- Crude estimate the Reynolds stress-driven flow
  - Assuming flow damping at ion transit rate

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

Production term conservatively transfers energy between non-zonal and zonal energy

Simplified energy balance equations

$$\partial_t \left(E_n + E_\sim\right) = \int dV \left[\frac{Q}{L_n} - \eta j^2 - T_{e0} \langle \phi \rangle \kappa(n_e) - n_0 m_i \langle \tilde{v}_r \tilde{v}_\theta \rangle \partial_r \langle \bar{v}_\theta \rangle \right]$$

GAM physics

Production term

$$\partial_t E_z = \int dV \left[T_{e0} \langle \phi \rangle \kappa(n_e) + n_0 m_i \langle \tilde{v}_r \tilde{v}_\theta \rangle \partial_r \langle \bar{v}_\theta \rangle \right]$$

- Equations capture the energy transfer that plays a key role in many models of the L-H transition.

Energy is transferred from mean flows to turbulence 1 cm inside the separatrix for all heating schemes

non-zonal ExB energy

$$\frac{n_o m_i \left\langle \tilde{v}_\theta^2 \right\rangle}{2}$$

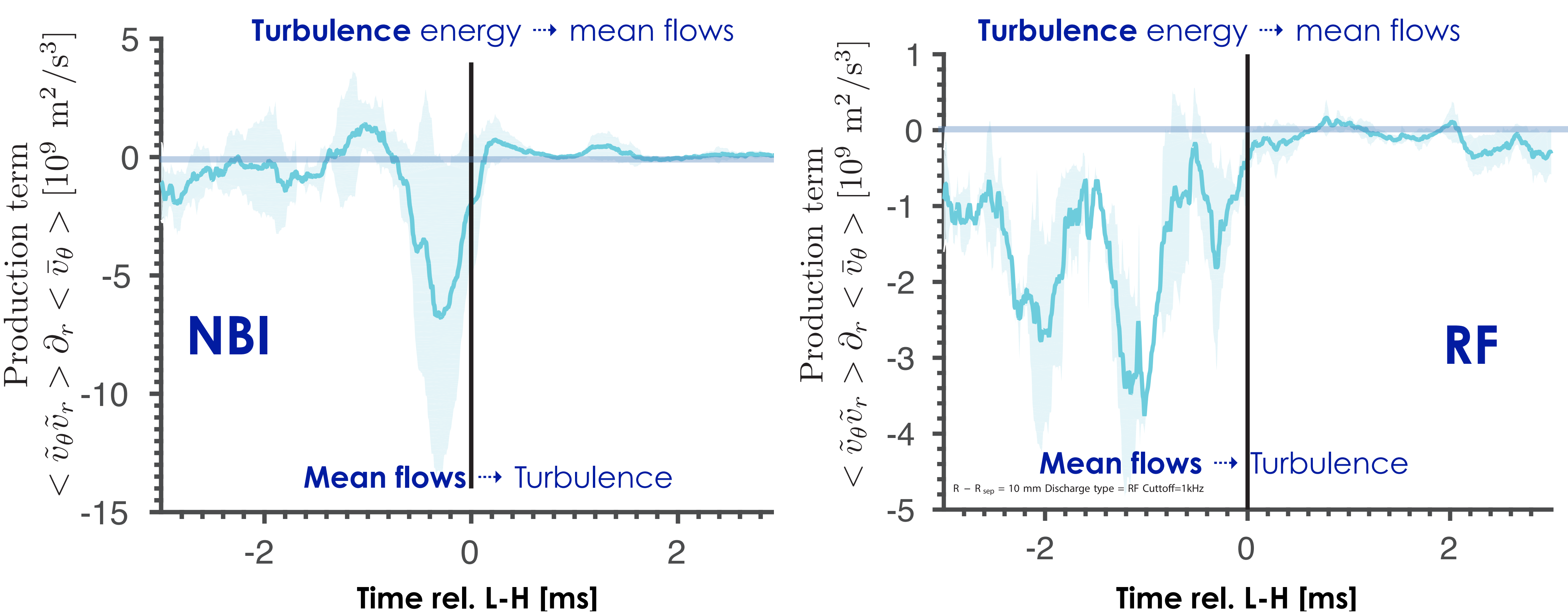
Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

Zonal ExB energy

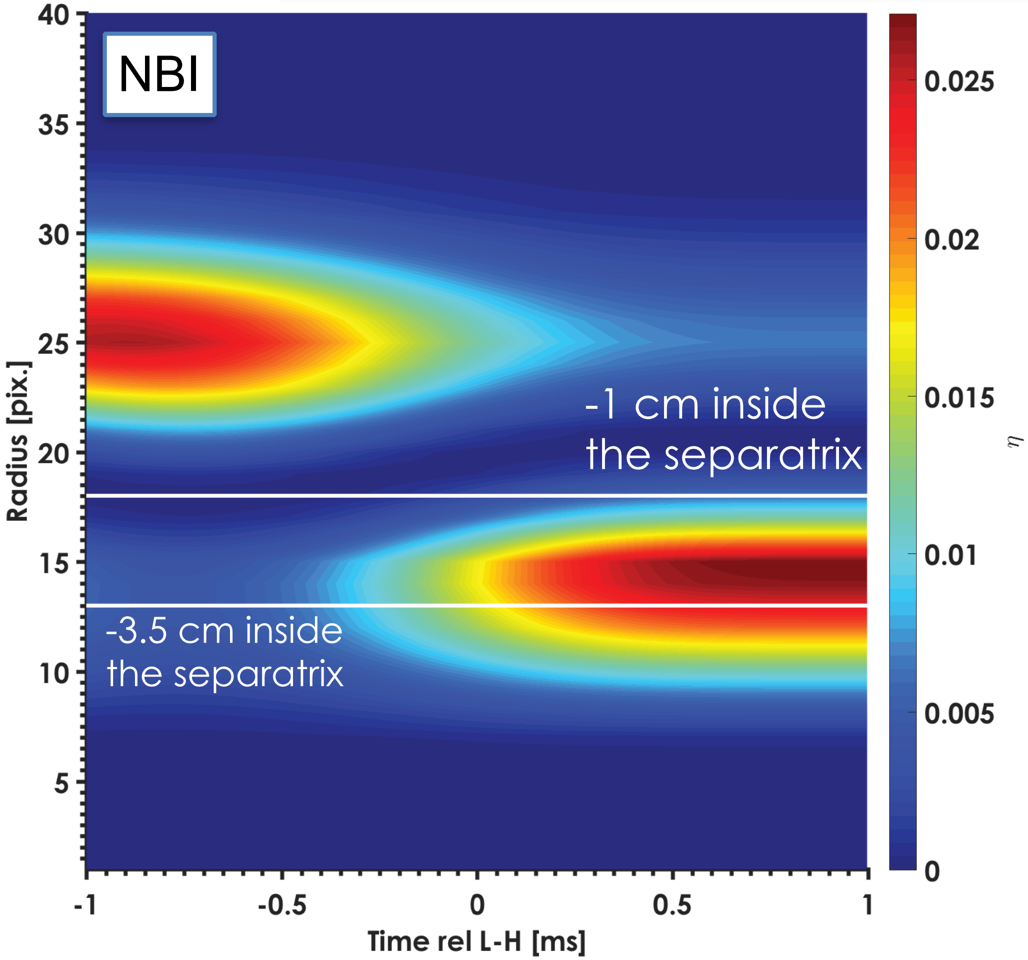
$$\frac{n_o m_i \left\langle \bar{v}_\theta \right\rangle^2}{2}$$

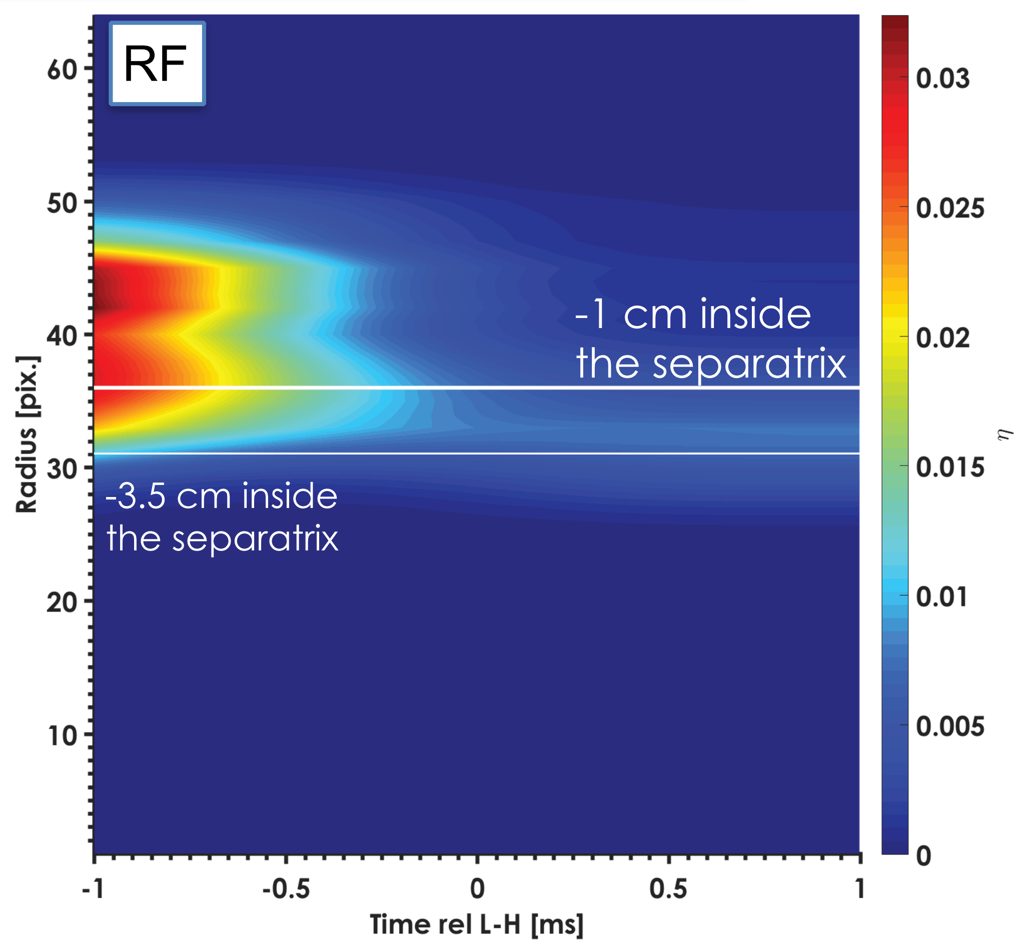
Production term



Kinetic energy in the mean flow is much smaller than the thermal free energy for <u>all discharges</u>

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





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,

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

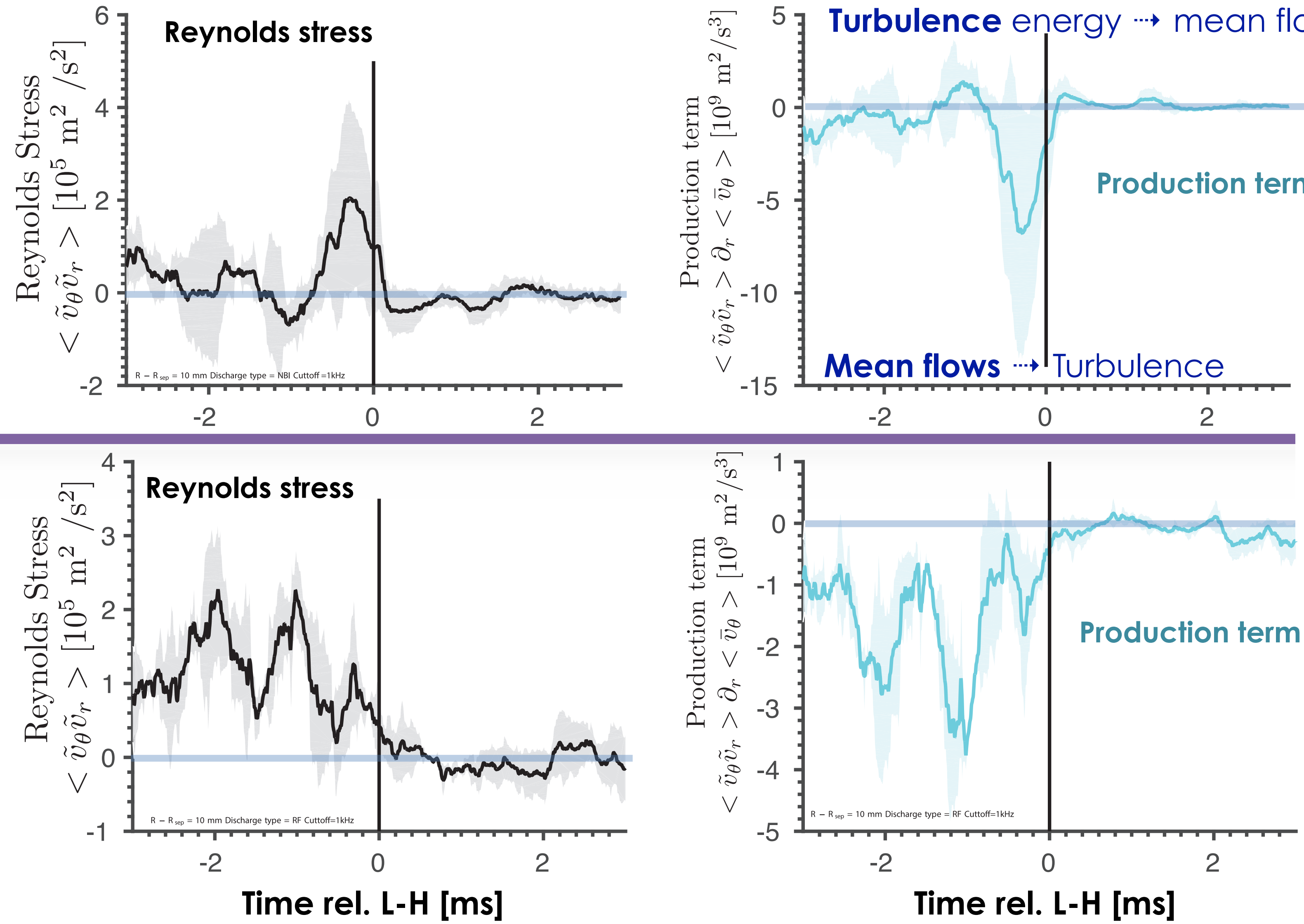
$$\text{High-pass filter of } v(r,\theta,t) \text{ at 1 kHz} \longrightarrow \tilde{v}(r,\theta,t)$$

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

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.

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



NBI

The shaded area represent the std over multiple discharges

RF

- 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.

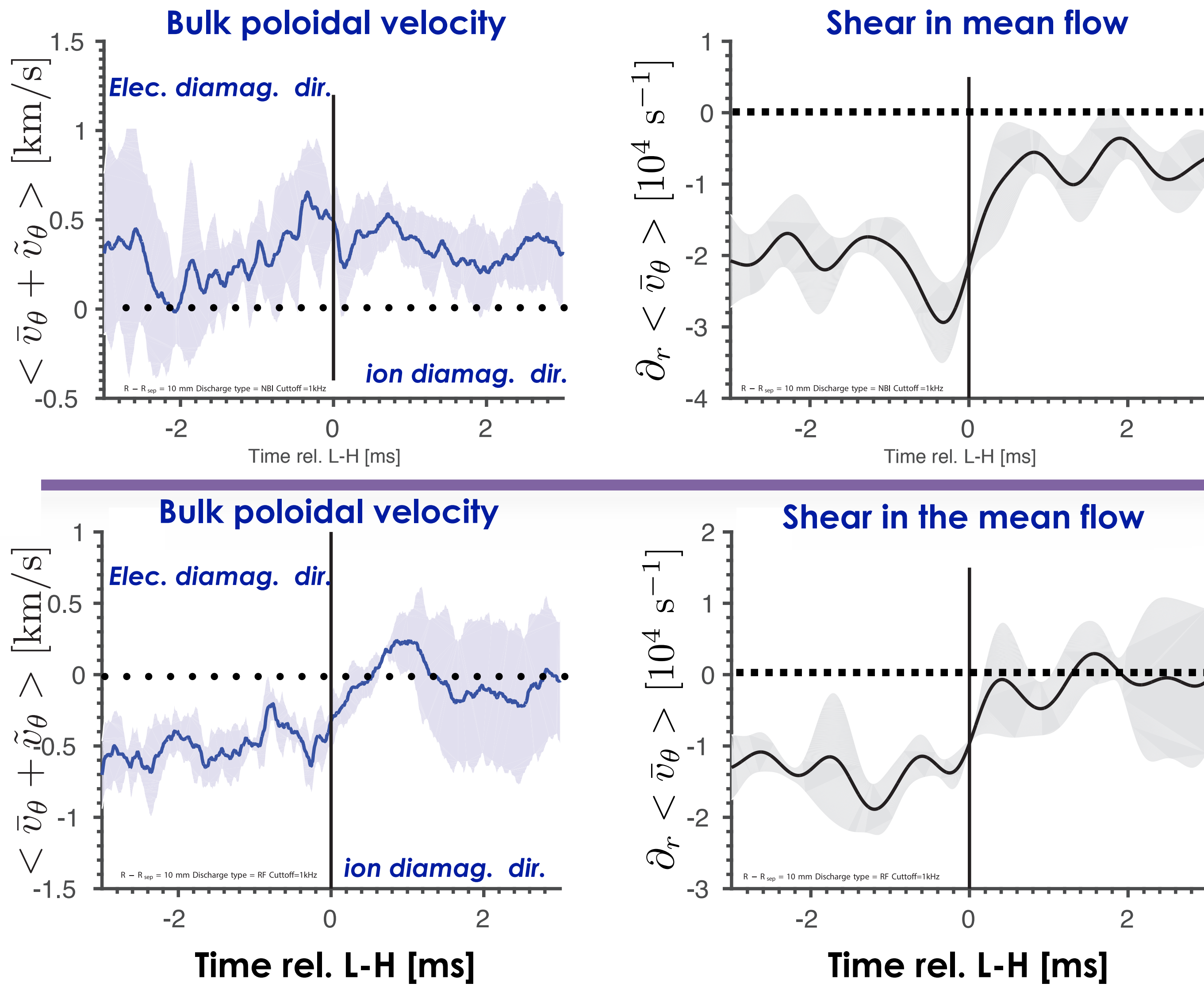
Sanchez JNM **337** 296 (2005)

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

NBI

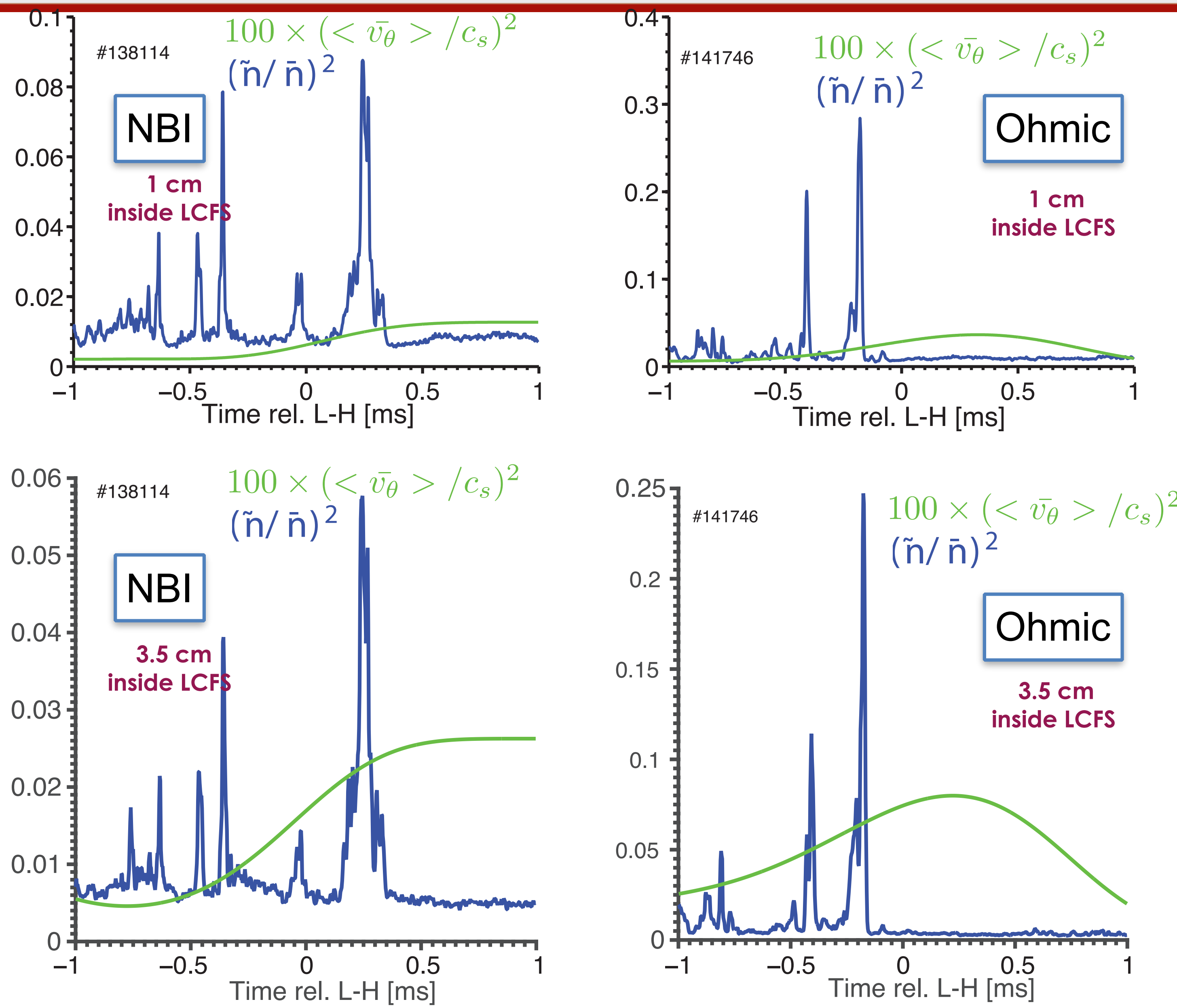
The shaded area represents the std over multiple discharges

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



The sum of the two turbulent fluctuation energies needs to be exhausted in order to deplete the turbulence

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

Electron parallel conduction
fast timescale

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

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

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

slow time scale

Production term

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

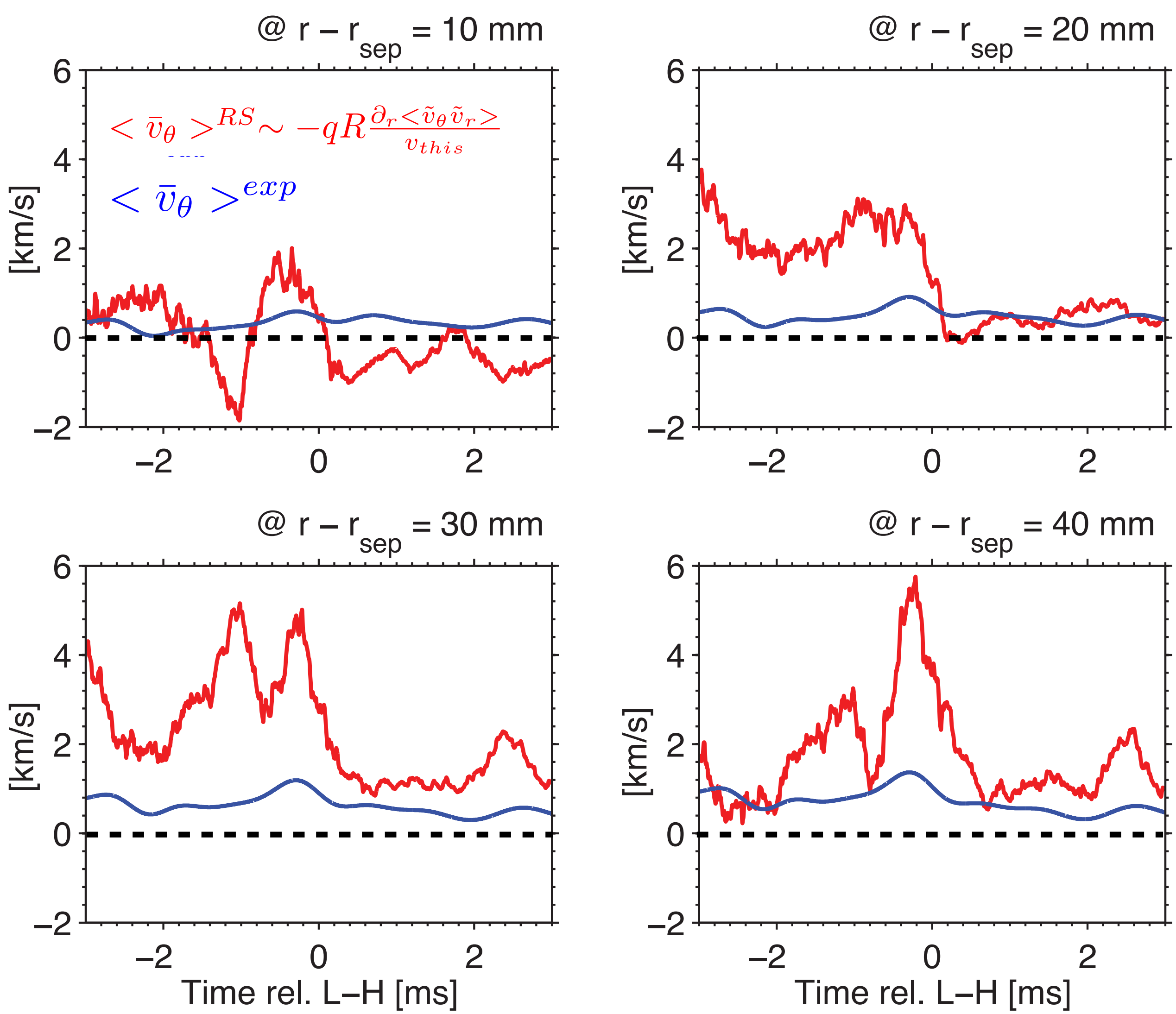
Moves as a single unit given the fast time scales $t \sim \frac{qR}{v_{the}}$

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

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

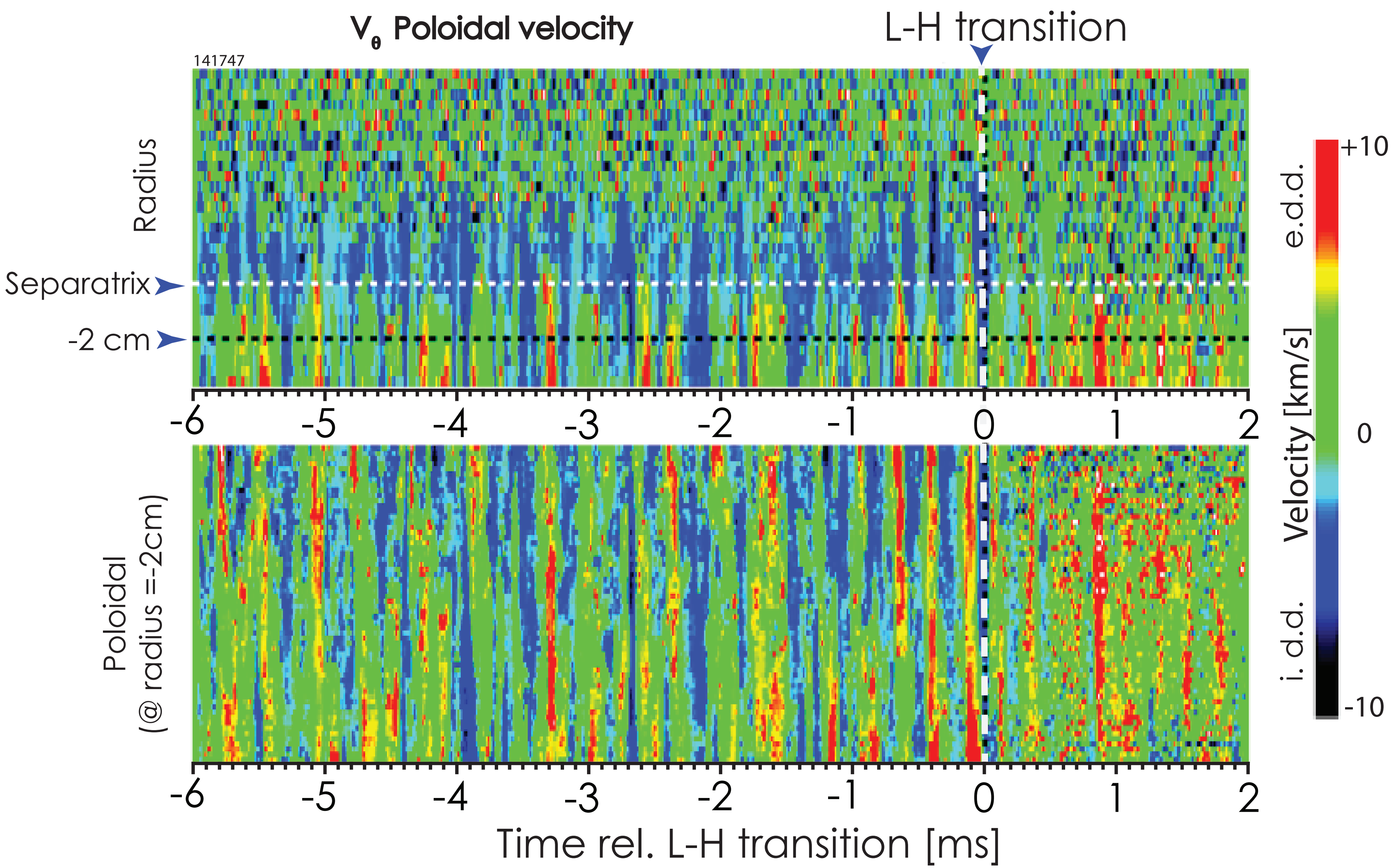
$$\frac{\left\langle \bar{v}_\theta^2 \right\rangle / c_s^2}{\left(\tilde{n}_e / n_{e0} \right)^2} \gtrsim 1$$

Reynolds stress-driven mean flow and the measured mean flow are of the same order of magnitude



- Crude estimate the Reynolds stress-driven flow
  - Assuming flow damping at ion transit rate
- **Contribution of the Reynolds stress to the mean flow cannot necessarily be discarded.**

Poloidal Flow



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

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

slow time scale

Production term

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

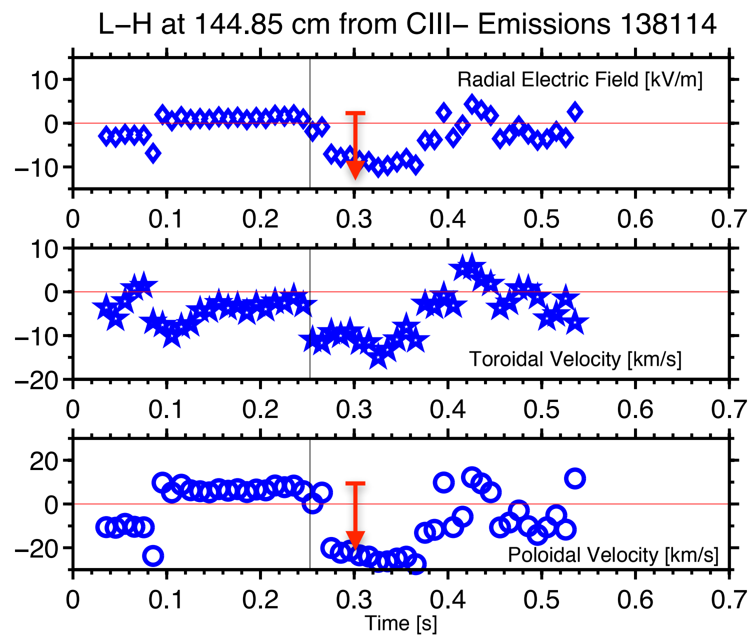
Moves as a single unit given the fast time scales $t \sim \frac{qR}{v_{the}}$

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

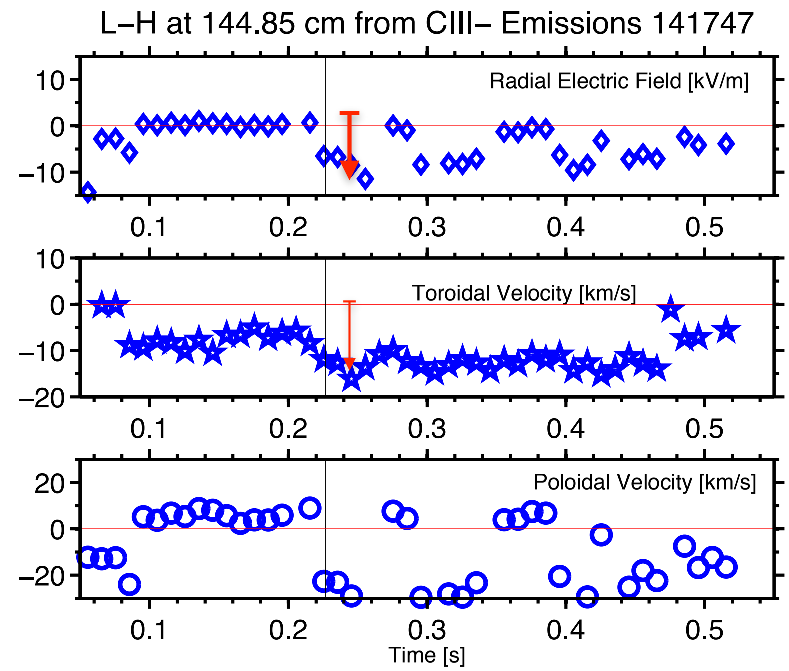
For energy transfer to mean flows to deplete the turbulence, we must have

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

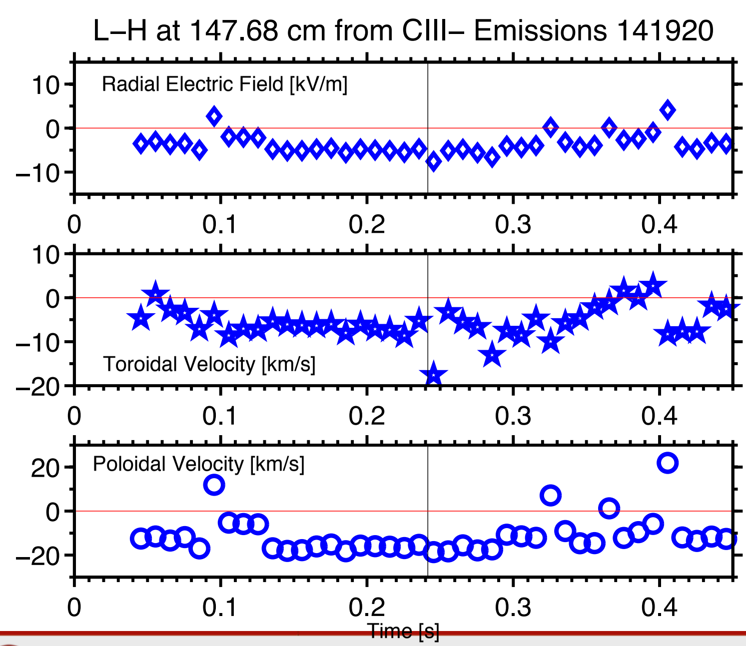
Clear drop in electric fields and velocities during the L-H transition, except for the RF heated discharges



NBI-heated



Ohmically-heated



RF-heated

- RF discharge has 4 cm gap while the NBI and Ohmic discharges have 8 cm
- The carbon poloidal velocities are different from to those derived from GPI
  - Can this hint at differences between fluid and turbulent flows?