Turbulent-driven Sheared ExB Flow as the Trigger for the H-mode Transition

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Summary

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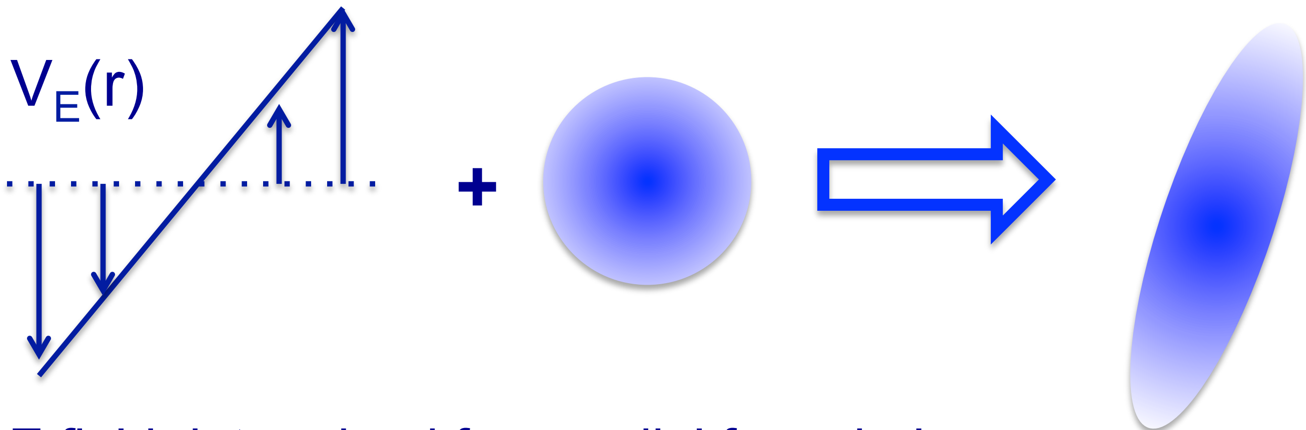
- New measurements reveal key role that ***turbulent-driven sheared ExB flows**** play in accessing H-mode, critical to ITER/fusion success
  - HL-2A L-mode
  - Limit-cycle-oscillation (LCO) regime stretches out transition in DIII-D
  - EAST L-H transitions
- Predator-prey model compares favorably to results
- Combined experiment/model insights should
  - Permit development of microphysics-based macroscopic model of transition threshold
  - Guide turbulence simulations to reproduce results

***Referred to as "Zonal Flows" in many quarters**

m,n=0 Sheared ExB Thought to Be Important for Edge Barrier….

Sheared E_r Can Tilt & Stretch Turbulent Structures or Eddies



Radial E field determined from radial force balance…

$$E_r = \frac{1}{ne}\nabla p_i - VxB$$

Does the turbulence itself create strong sheared E_r and thus initiate the transition process?

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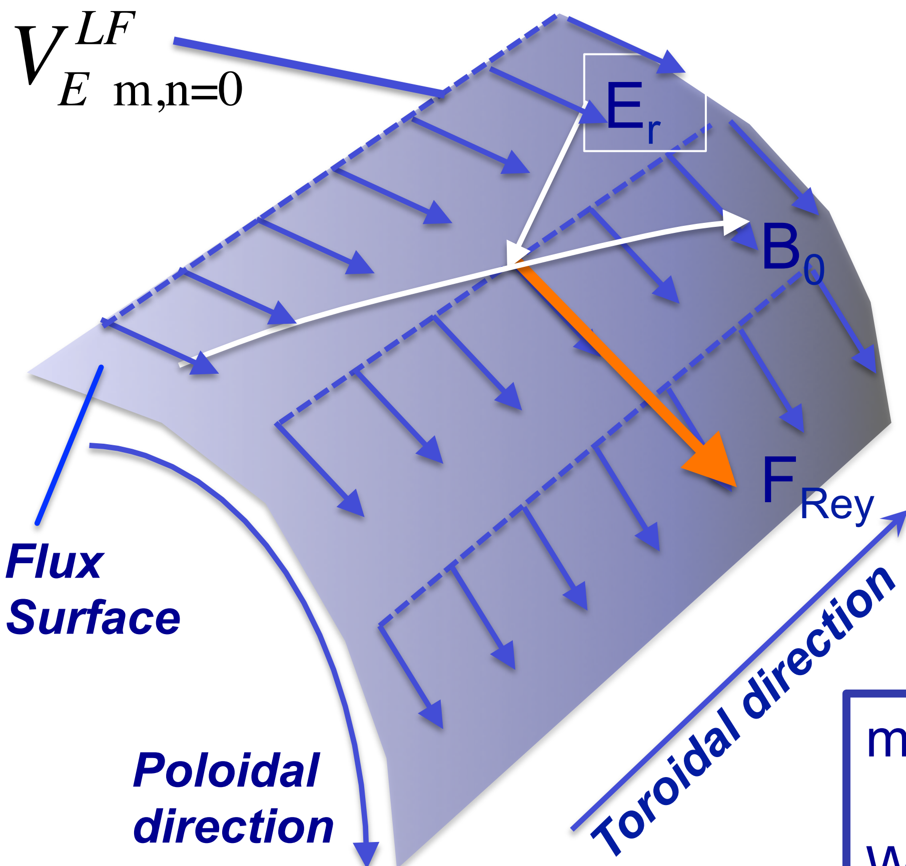
Turbulence Can Drive the m,n=0 ExB Shear Flow:



Poloidal Component of **Reynolds Force:**

$$F_{\theta_{\text{Rey}}} = -\frac{\partial}{\partial r}\langle \tilde{v}_r \tilde{v}_\theta \rangle$$

Rate of work done by turbulence on low frequency (LF) m,n=0 ExB:

$$P_{LF} = -\frac{\partial}{\partial r}\langle \tilde{v}_r \tilde{v}_\theta \rangle V_{ExB}^{LF}$$

m,n=0 ExB causes no transport

Work done on m,n=0 ExB comes ***at the expense of the turbulence energy & leads to reduced rate of transport***

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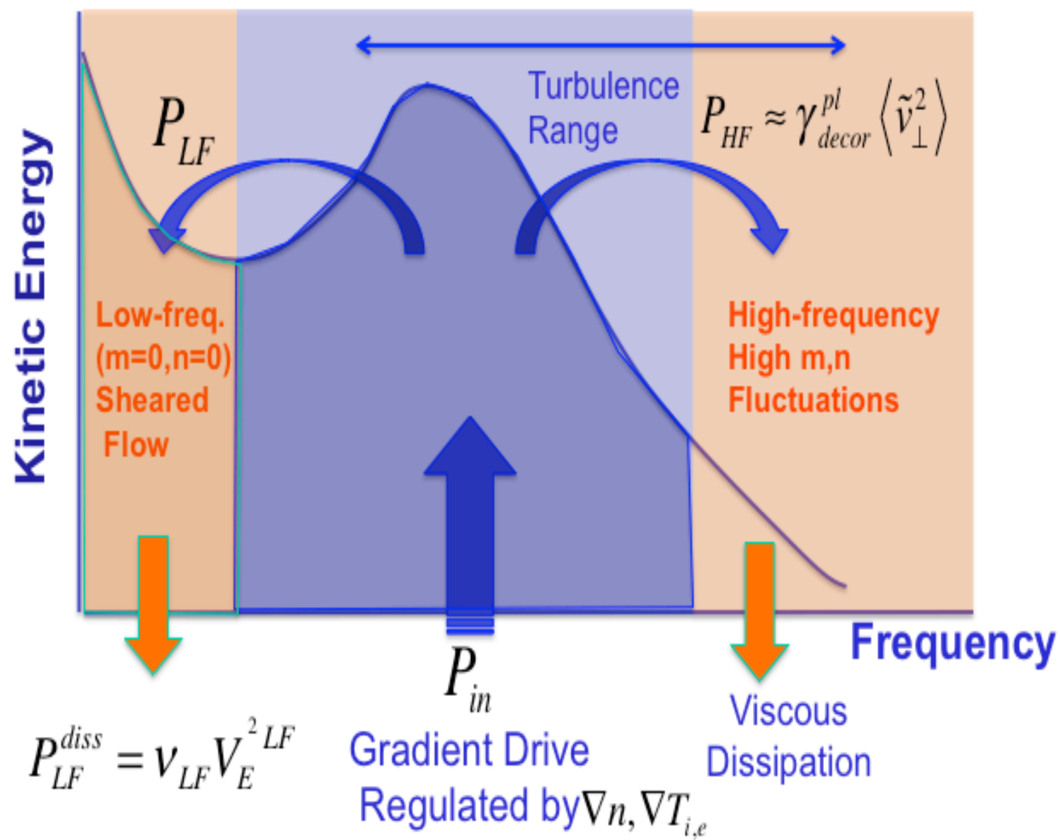
Process can be viewed as a power balance between spatio-temporal scales

Turbulent scale (broadband m,n > few; f>20-30 kHz)

$$\frac{\partial\langle\tilde{v}^2\rangle}{\partial t} = P_{in} - P_{HF} - P_{LF}$$

Low-Frequency (LF) m,n=0 ExB scale [**Sink** for Fluctuation energy]

$$\frac{\partial V_{ExB}^{LF^2}}{\partial t} = P_{LF} - P_{LF}^{diss}$$



Turbulent transport & m,n=0 ExB flow set by this power balance

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New multi-point probe arrays used to provide stress & m,n=0 ExB flow measurements inside LCFS

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Probes (& BES for L^{corr}) Measure

$$\gamma_{decorr}^{pl} = \gamma_{decorr}^{lab} - V_{ExB} / L_{\theta}^{corr}$$

$$\langle \tilde{v}_{\perp}^{2} \rangle$$

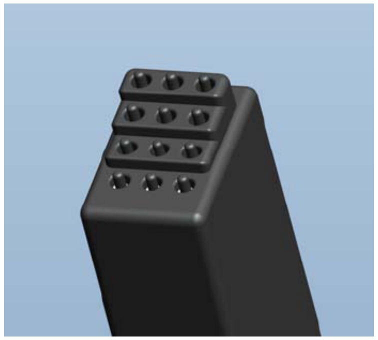
$$\langle \tilde{v}_{r} \tilde{v}_{\theta} \rangle$$

$$V_{ExB}^{LF} \text{ includes } f < f_{c}^{m,n=0} \sim 5kHz$$

$$\text{assuming that } \vec{v} = \frac{-\vec{\nabla}\phi_{fl} \times B}{B^{2}}$$

Complement w/ BES, DBS, …
Fluctuation diagnostics

New Multi-point arrays:



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Experiments show that this actually occurs

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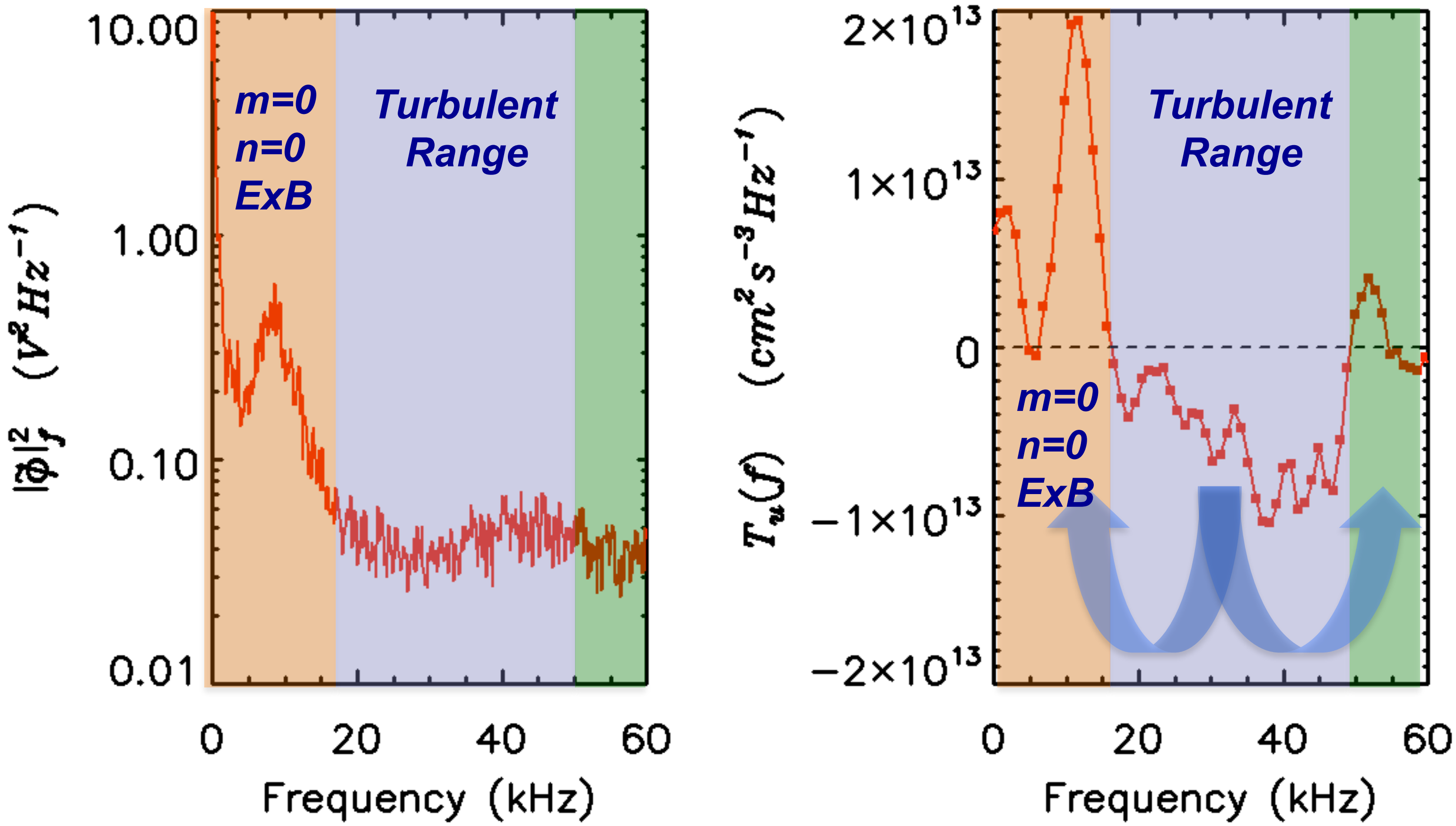
1 cm inside LCFS of ECH heated Limiter Plasma



See M. Xu PRL '12 for flow drive physics; also M. Xu PoP'10
See K. Zhou, PRL'06, PPCF'11 for identification of m/n=0/0 structure

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Expected turbulence & m,n=0 ExB flow behaviors:

L-mode when $P_{LF} \leq P_{LF}^{diss}$

$$\left(\text{i.e. } \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle' V_{ExB}^{LF} < \nu_{LF} V_{LF}^2 \right)$$

LCO Regime when $P_{in} - P_{HF} > P_{LF} > P_{LF}^{diss}$

$$\left(\text{i.e. } \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle' V_{ExB}^{LF} > \nu_{LF} V_{LF}^2 \right)$$

H-mode when $P_{LF} > P_{in} - P_{HF}$

$$\left(\text{i.e. } \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle' V_{ExB}^{LF} > \left(\gamma_{eff} - \gamma_{decorr} \right) \left\langle \tilde{v}_\perp^2 \right\rangle \right)$$

[Manz, PoP12]

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HL2A: ECH L-mode Plasmas

Strength of m,n=0 ExB Shear Flow Drive Increases with P_{aux} inside the LCFS

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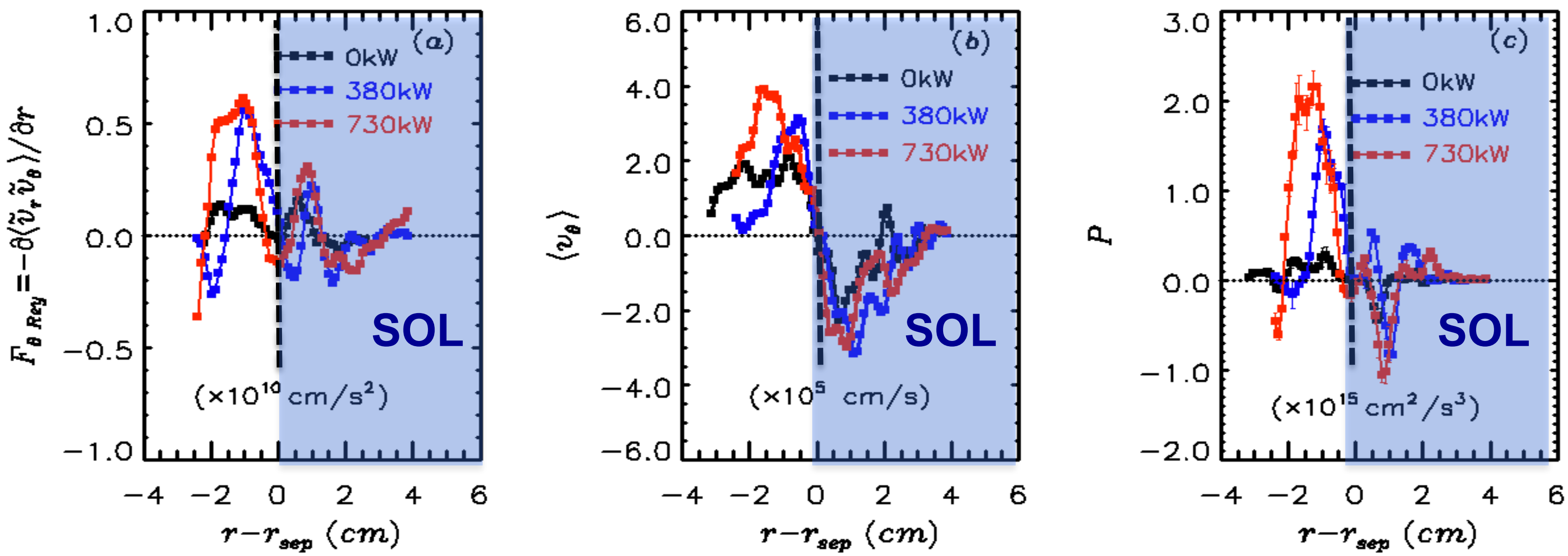
Ref: M. Xu, PRL'12

Reynolds Force

Poloidal ExB Drift Profile

Rate of Work by Turbulence on LF m,n=0 ExB



What happens with further increases of heating power?

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DIII-D: L-mode to LCO (a.k.a. I-phase) Transition Studies

LCO Characterized by m,n=0 ExB Oscillations & Modulation of Turbulent Fluctuation Amplitude

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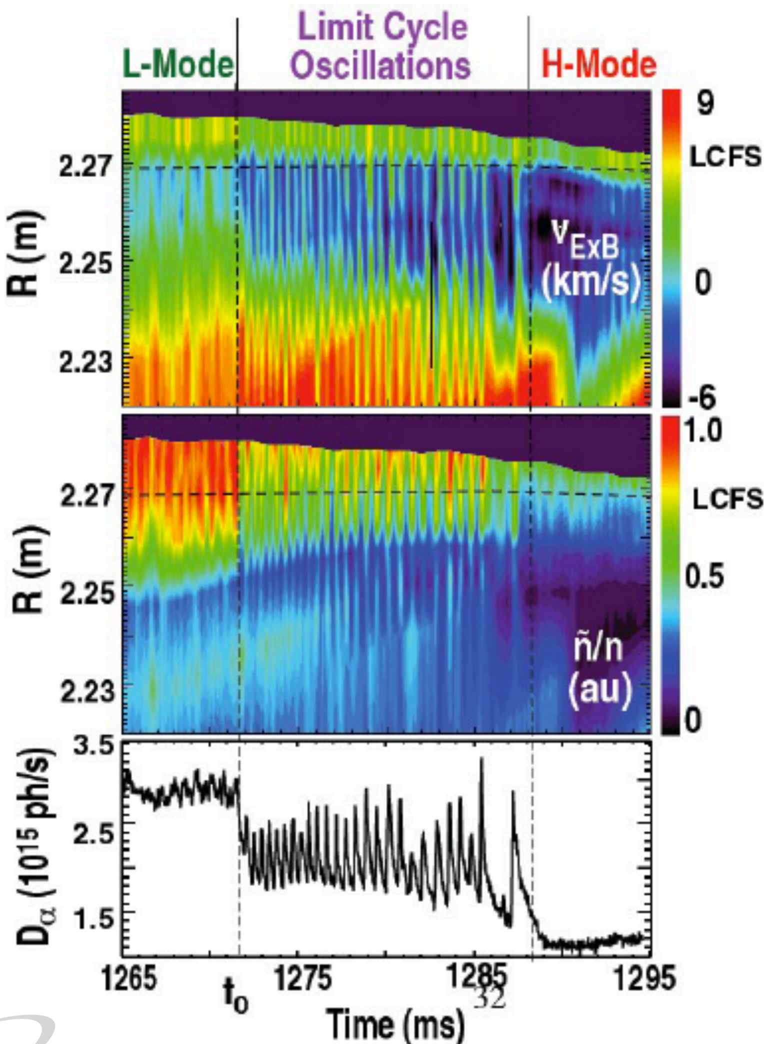
Schmitz et al, PRL'12



- LF Sheared ExB Flow Oscillations in LCO
- Turbulent Fluctuation Amplitude Modulated in LCO
- LCO Dynamics Localized to ~2-3cm Inside LCFS
- LCO Gives Way to Steady-state H-mode w/ ExB Shear & Reduced Transport

Sheared m,n=0 ExB is **Driven by Turbulent Stress**

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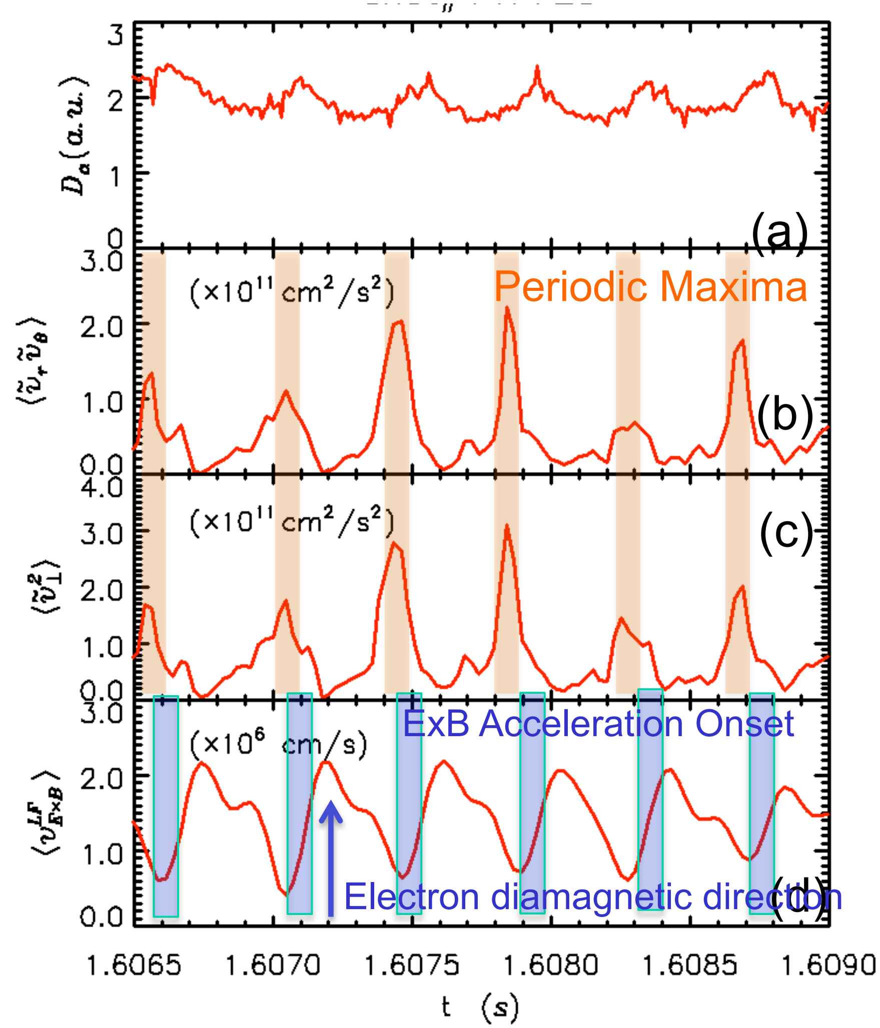
- Turbulent stress modulated w/r/t m,n=0 ExB
- Max stress gives onset of max. V_{ExB}^{LF} acceleration
- Peak $V_E \sim \pi/2$ delay w/r/t Turbulence
- V_{ExB}^{LF} *rises faster than It decays*

1cm inside LCFS of NBI-heated LSN Discharge



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m,n=0 ExB Flow Becomes **Dominant Turbulent Power Loss Channel** in LCO Regime

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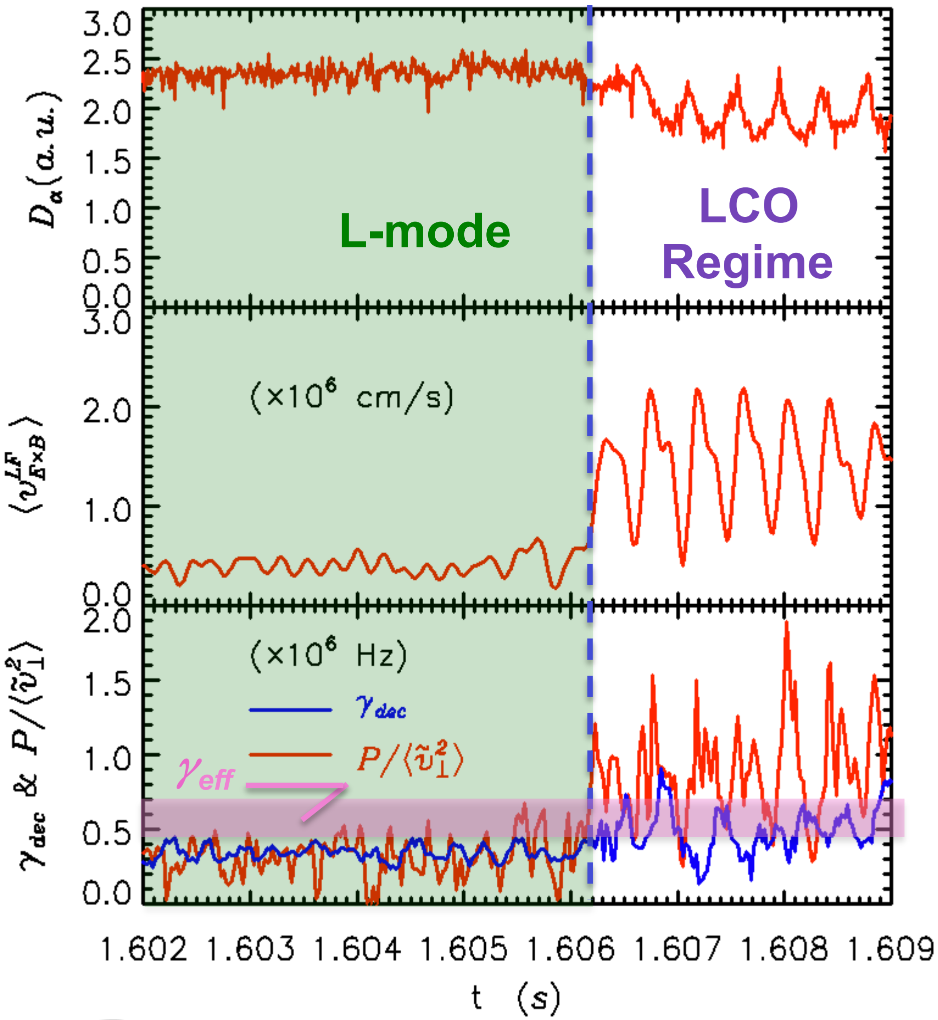
1cm inside LCFS of NBI-heated LSN Discharge



- Equipartitioned power transfer in L-mode
- Power transfer rate to ExB shear flow increases when LCO starts
- ExB shear flow becomes dominant turbulent power loss channel in LCO regime
- In LCO, max. P_{LF}/v^2 value exceeds L-mode energy input rate & rapidly drains turbulent energy

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DIII-D: LCO TO H-mode Transition

Grad-P_i component of ExB grows as LCO progresses

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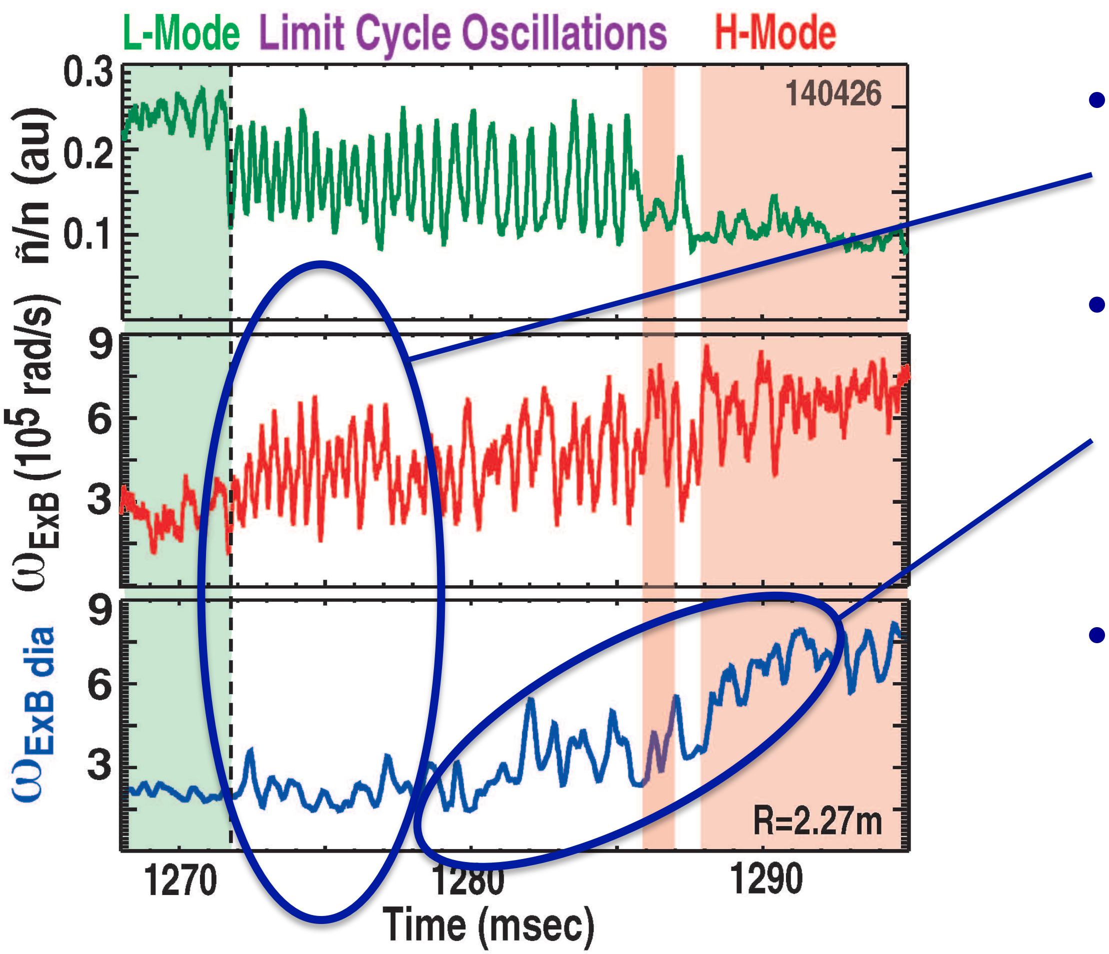
Ref: L. Schmitz, PRL '12



- Total ω_{ExB} larger than grad-P_i component, $\omega_{ExB\ dia}$ early in LCO
- $\omega_{ExB\ dia}$ Gradually Becomes Large Enough to Impact Turbulence (Schmitz, PRL'12)
- Suggests transition from Zonal Flow to Mean-shear flow regime during LCO

Strong power transfer into m,n=0 ExB shear flow is locked in during H-mode

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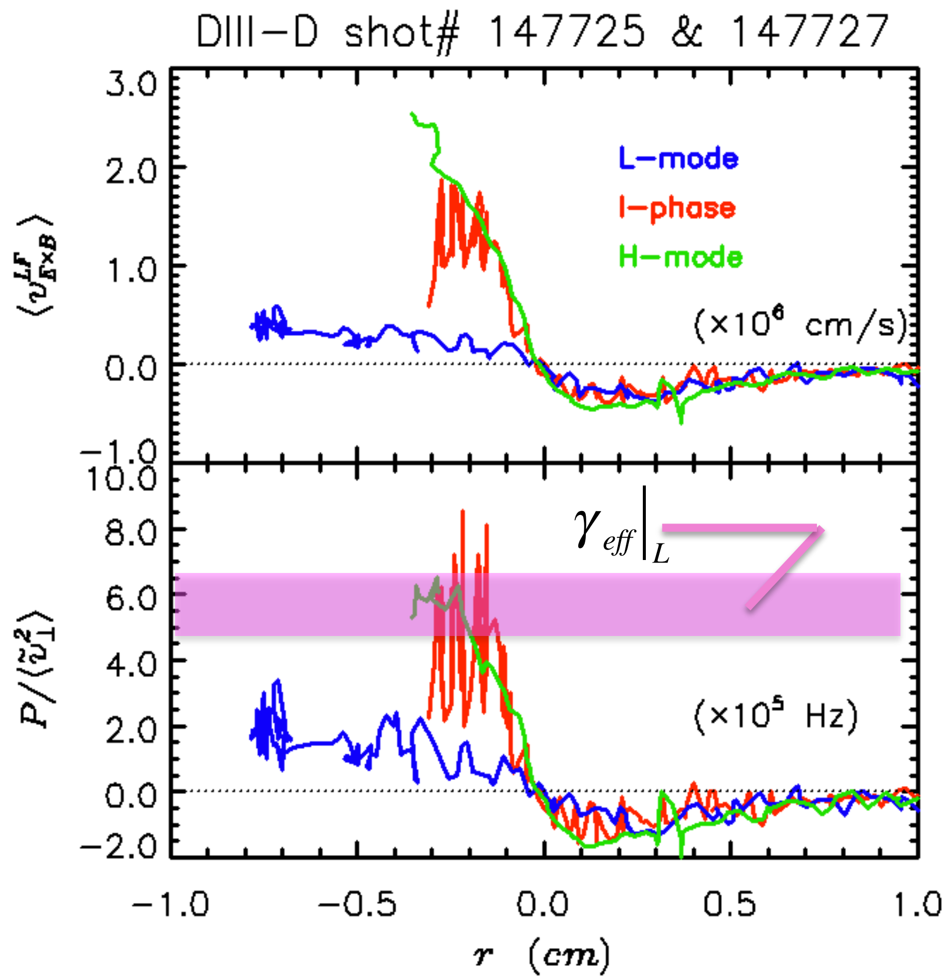
- LF ExB profile oscillates in LCO phase; peak values approach H-mode values
- Transfer rate to LF ExB in LCO oscillates around H-mode values
- H-mode locks into upper range of LCO transfer rate, close to L-mode γ_{eff}



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EAST: L-H Transition Studies

Power transfer to m,n=0 ExB plays key role in L-H transition

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Turbulence Collapses when: $P_{LF} > P_{in} - P_{HF}$

$$\left(\text{i.e. when } \frac{\langle \tilde{v}_r \tilde{v}_\theta \rangle V'_{ZF}}{\langle \tilde{v}_\perp^2 \rangle \left(\gamma_{eff} - \gamma_{decorr} \right)} > 1 \quad ==> \quad \langle \tilde{v}_\perp^2 \rangle \propto e^{-t/\tau} \right)$$

Net energy input rate $\left(\gamma_{eff} - \gamma_{decorr} \right)$ determined from LCO regime w/ same edge gradients…

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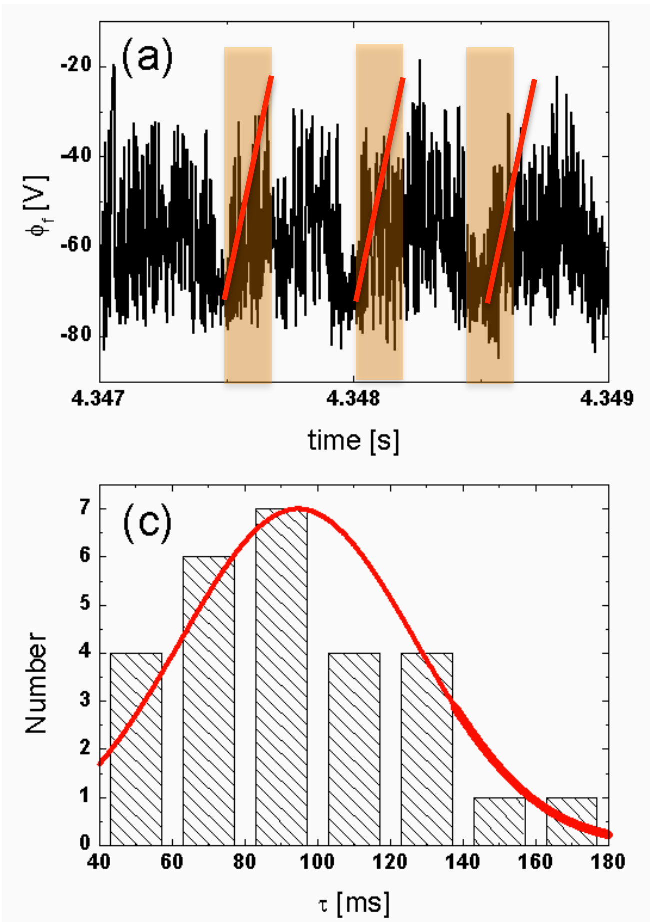
Determine Power Input into Turbulence from Turbulence Energy Recovery Rate in LCO Regime

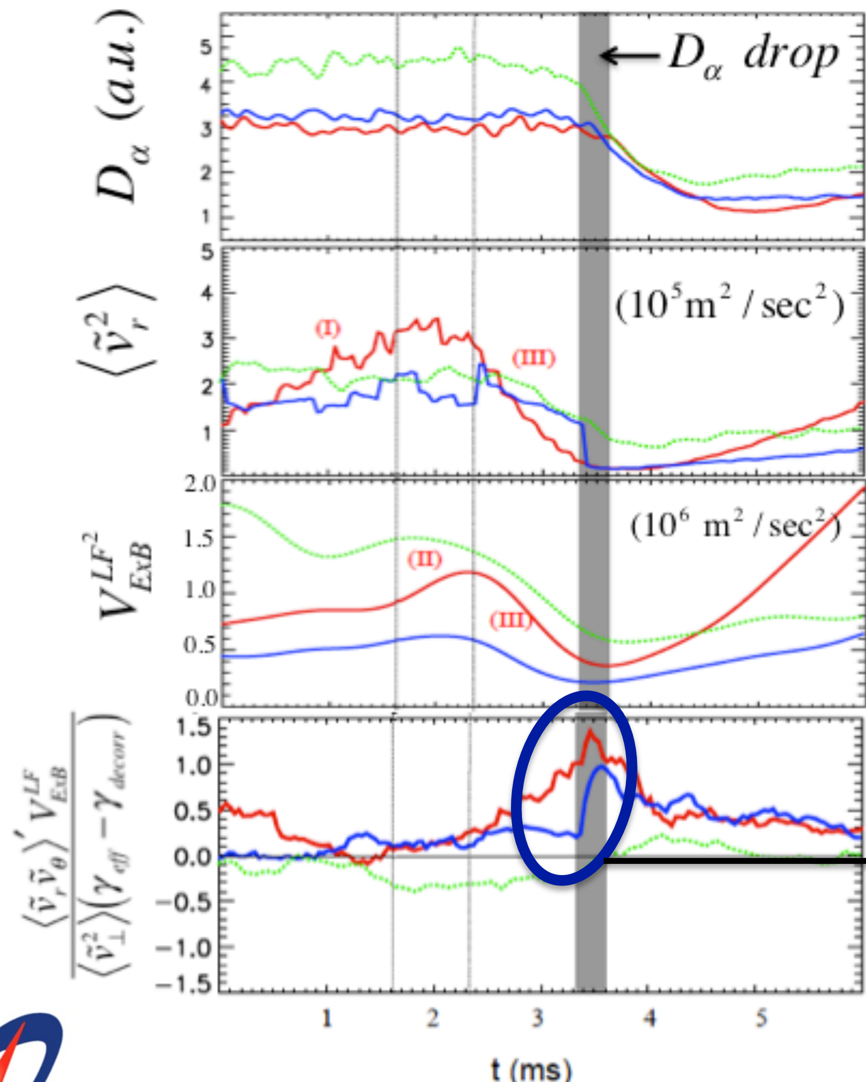
Turbulence Recovery Timescale in EAST LCO Regime



- Identify LCO regime with same macroscopic parameters & edge gradients
- Measure turbulence recovery rate when m,n=0 ExB flow is small
- Use recovery rate in analysis of L-H transition

Manz et al, PoP '12

L-H Transition When m,n=0 LF ExB Drive Exceeds Energy Input Rate into Turbulence



- Turbulence Energy & LF ExB Energy Increase
- Power Transfer Increases
- Power Transfer Grows to ~Equal Turbulent Energy Input Rate
- L-H Transition Occurs

$$\langle \tilde{v}_r \tilde{v}_\theta \rangle V'_{ZF} \approx \left(\gamma_{eff} - \gamma_{decorr} \right) \tilde{v}_\perp^2$$

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Comparison to Predator-Prey Model

Predator-Prey Reduced Model

POWER BALANCE MODEL

$$\frac{\partial \tilde{v}_\perp^2}{\partial t} = \gamma_{eff}\tilde{v}_\perp^2 - \gamma_{decorr}^{pl}\tilde{v}_\perp^2 - \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle' V_{ExB}^{LF}$$

$$\frac{\partial V_{ExB}^{LF^2}}{\partial t} = \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle' V_{ExB}^{LF} - \nu_{LF} V_{ExB}^{LF^2}$$

K&D PRL'03 closed this system to form a reduced model with following:

$$\left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle \propto \frac{\bar{V}_{ExB}'^{LF}}{1+\alpha \bar{V}_E'^2} \quad q \propto -\left\langle \tilde{v}_\perp^2 \right\rangle \tau_{corr} \nabla p_i \quad \bar{V}_{ExB}' \propto \nabla p_i$$

$$\gamma_{eff} = \gamma_{eff}(\nabla n, \nabla T, \bar{V}_E')$$

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Slow Power Ramp Gave an LCO State Leading to H-mode….

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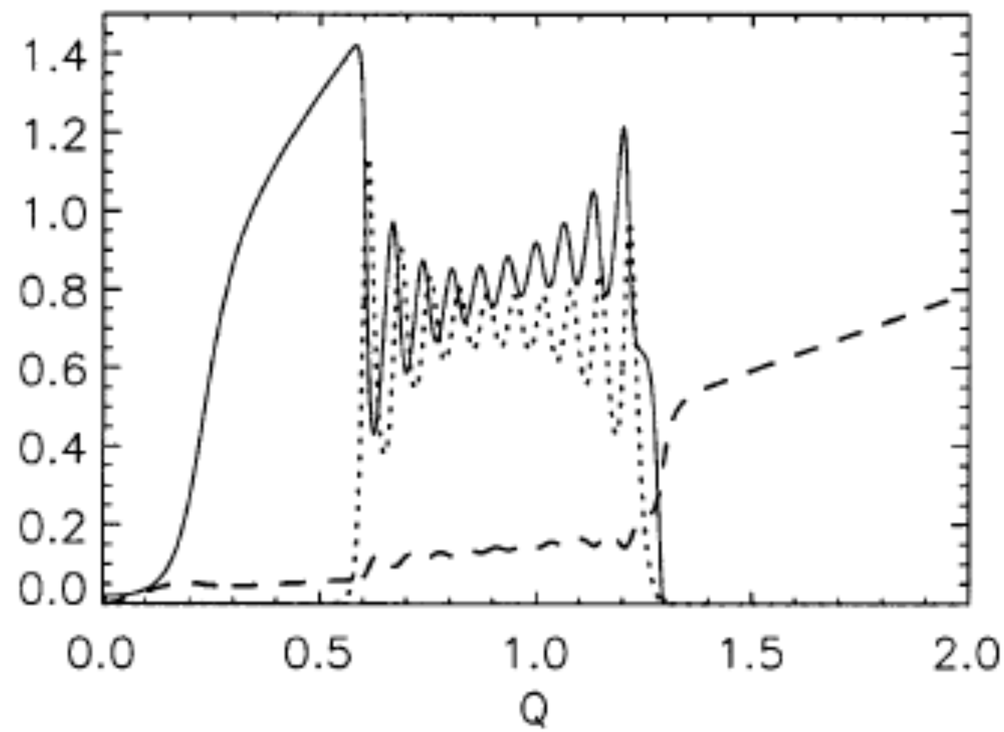
Kim & Diamond, PRL'03

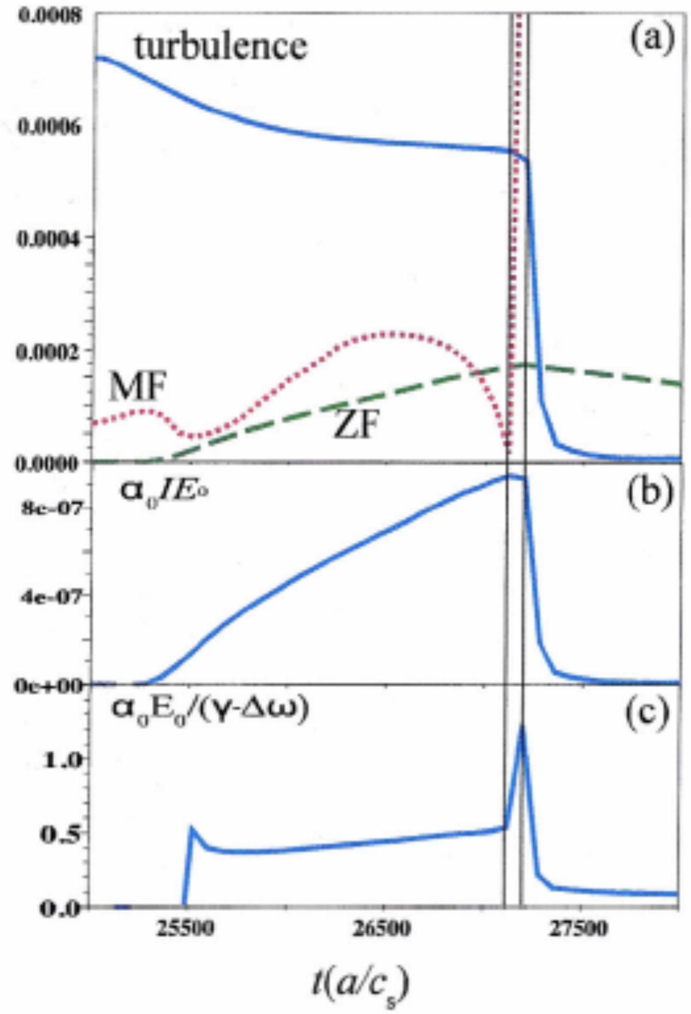
- Low heating ➔ L-mode state
- Intermediate heating ➔ LCO state w/ strong Zonal Flow & Turbulence Modulations
- Strong heating ➔ Collapse of turbulence & Zonal Flow, Rise of mean flow➔ H-mode



Predator-Prey Model Reproduces Observed L-H Transition Dynamics

Manz, PoP'12;
Miki & Diamond PoP'12.

- Turbulent-driven m,n=0 ExB ("Zonal Flows") builds up & regulates turbulence
- Reduction in transport builds up grad-P_{ion} ExB flow
- P_{LF} grows; when turbulent drive is exceeded turbulence collapses
- Turbulent-driven m,n=0 ExB decays
- Strong grad-P_{ion} ExB flow locks-in H-mode



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Conclusions:

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- In L-mode Rate of Power Transfer from Turbulence into m,n=0 ExB Flow Increases w/ P_{aux}
- LCO Onset When Power Transfer in m,n=0 ExB Flow Becomes Dominant Turbulent Energy Sink
- Turbulent stress drives the m,n=0 ExB Flow in early LCO; Effects Isolated to just inside LCFS
- grad-P_{ion} component of LF m,n=0 ExB flow grows in LCO regime and dominates at transition to H-mode
- H-mode locks-in strong power transfer
- L-H transition is the limiting case of this more general phenomena
- Results Compare Favorably to KD'03 Predator-Prey Model

Questions & Open Issues

- Independent Confirmation is Needed
- Results Imply Threshold Linked to turbulent-driven m,n=0 ExB Flow Damping
  - What happens when neutral recycling recovers in long pulse machines? Can we stay in H-mode or Recover an H-mode?
- Use Insights to Move Past Empiricism and Build a Macroscopic Power Threshold Model Based on Turbulence Physics
- Need to Isolate Role of Slow Gradient Buildup in LCO in Locking in H-mode
  - Need to Separate VxB and grad-P_{ion} Contributions
- Insights Can Guide Turbulence Simulations of L-H Transition & Allow Them to Reproduce Results; Simple Fluid models Should Suffice for the Physics & GK can Fill in Discharge-specific Details

BACKUPS

LCO Characterized by m,n=0 ExB scale & Turbulent-scale Kinetic Energy Oscillations

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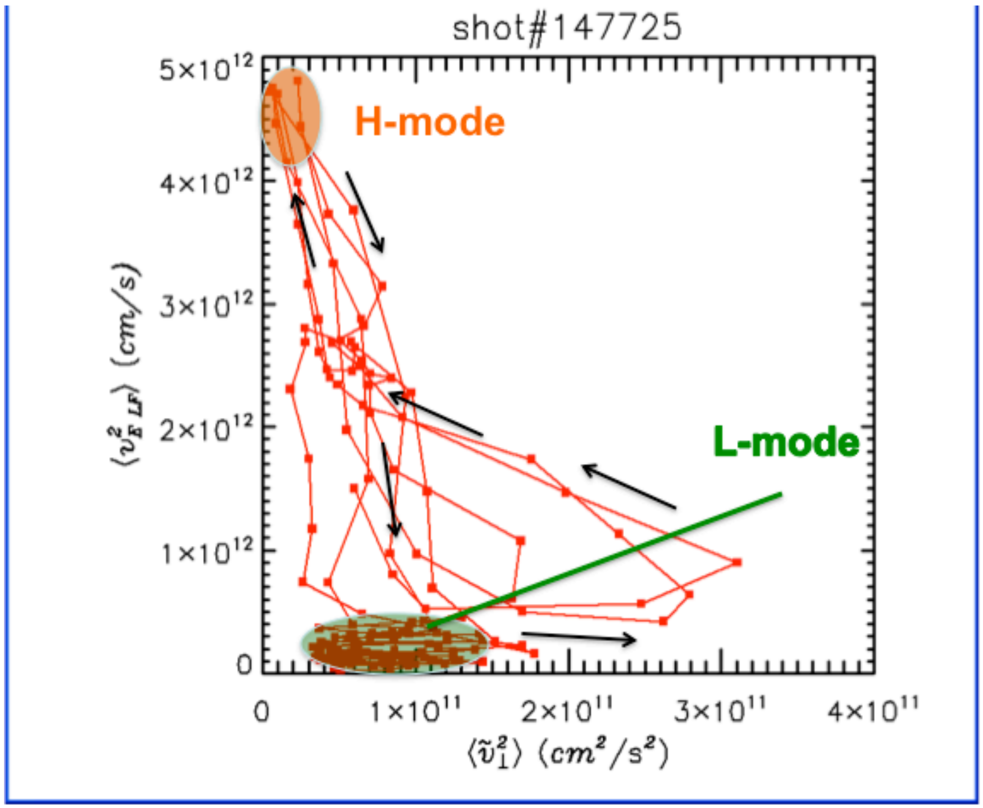
1cm inside LCFS of NBI-heated LSN Discharge



- Turbulent fluctuation amplitude & m,n=0 sheared ExB flow are modulated in LCO
- System oscillates between L-mode & near H-mode conditions
- Turbulence suppressed in H-mode by steady-state ExB shear
- Dynamics localized to ~2-3cm inside LCFS

ref: Schmitz PRL'12

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Probe & BES Velocimetry Give Similar Results

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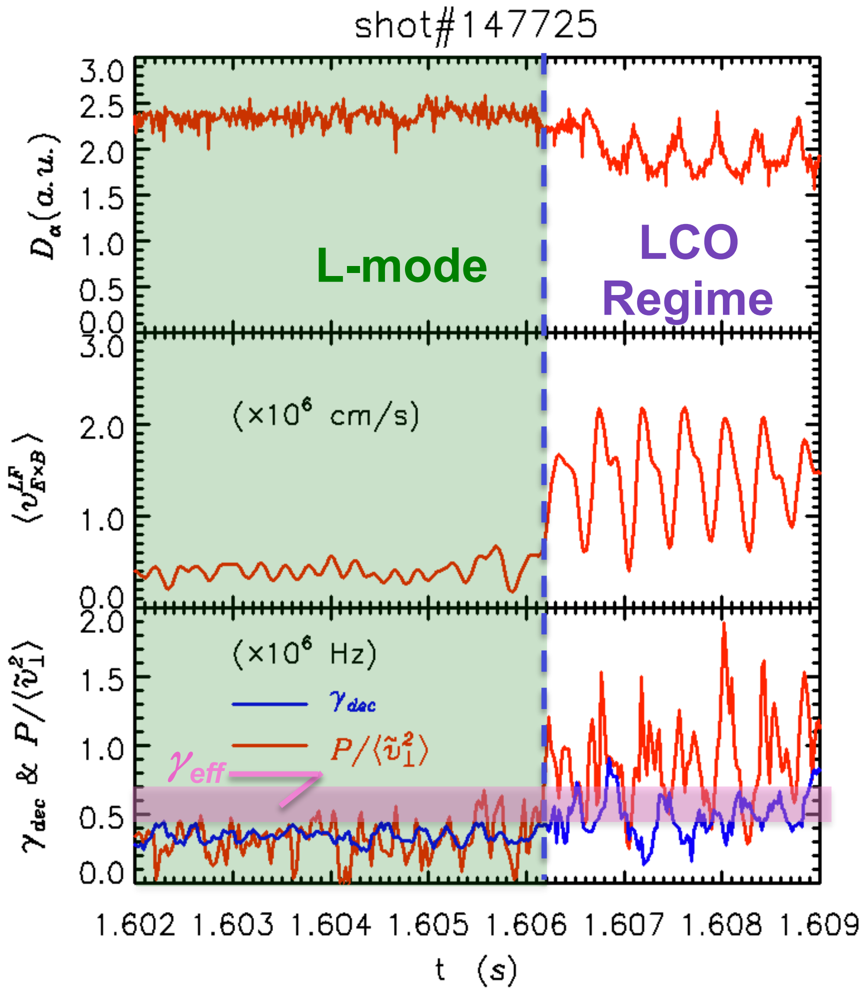
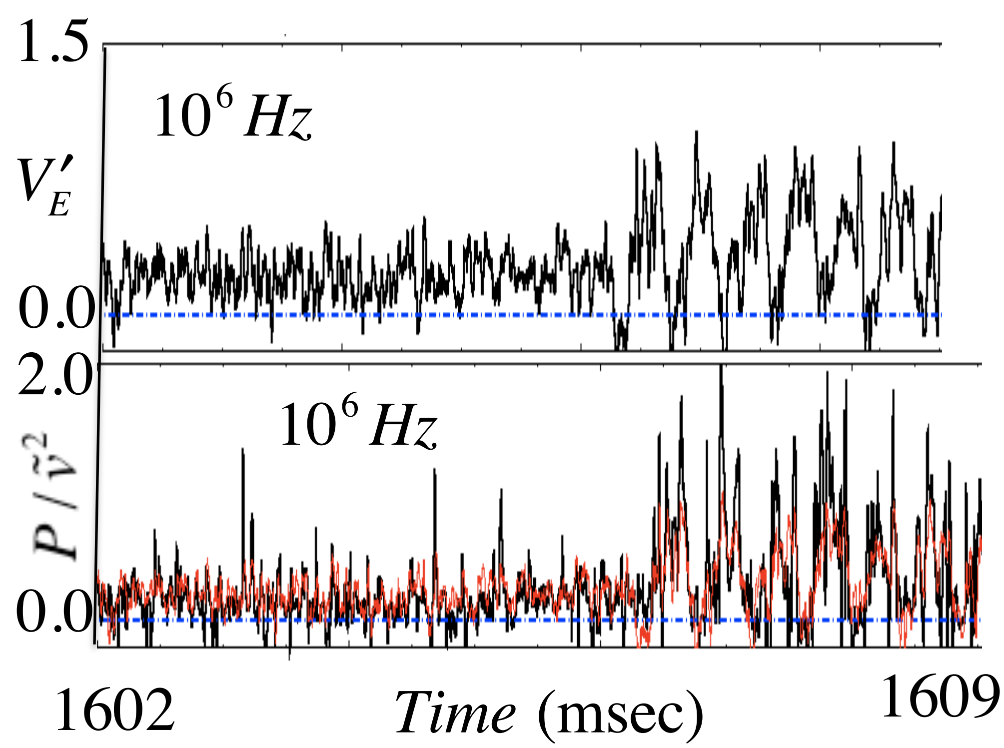
Probe Results



BES Results

PRELIMINARY

Z. Yan & G. McKee, Private Comm.



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Turbulent Stress (disordered small scale) can Drive Flows (large scale ordered)

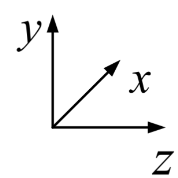
Force balance
On fluid element:

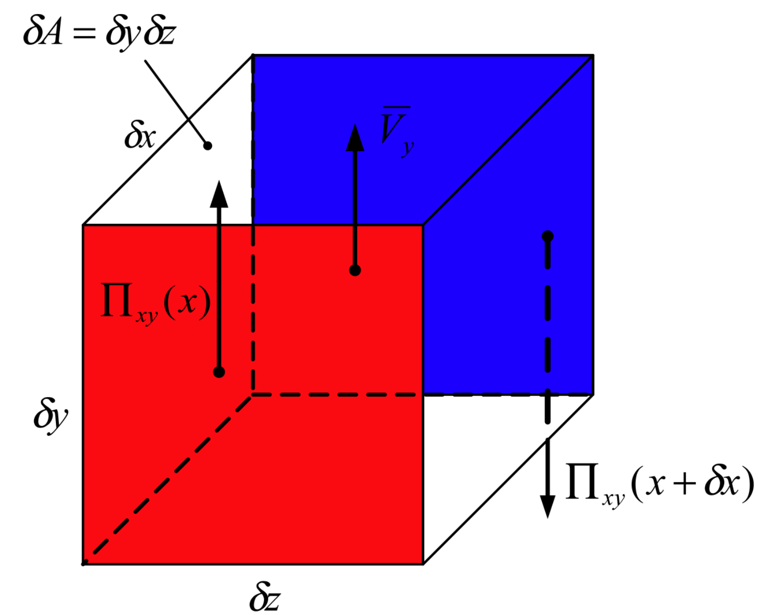
$$dF_y = [\Pi_{xy}(x+\delta x) - \Pi_{xy}(x)]dA$$

Turbulent momentum conservation eqn:

$$\frac{\partial \langle \mathbf{V} \rangle}{\partial t} = -\nabla \cdot \overleftrightarrow{\Pi}_t - \nu \langle \mathbf{V} \rangle + \ldots$$

$$\overleftrightarrow{\Pi}_t = \langle \tilde{\mathbf{v}}\tilde{\mathbf{v}} \rangle - \frac{\langle \tilde{\mathbf{b}}\tilde{\mathbf{b}} \rangle}{mn\mu_0}$$





Divergence of Turbulent Stress Can Amplify Flow!

BACKUP

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