First Direct Evidence of Turbulence-Driven Main Ion Flow Triggering the L-H Transition

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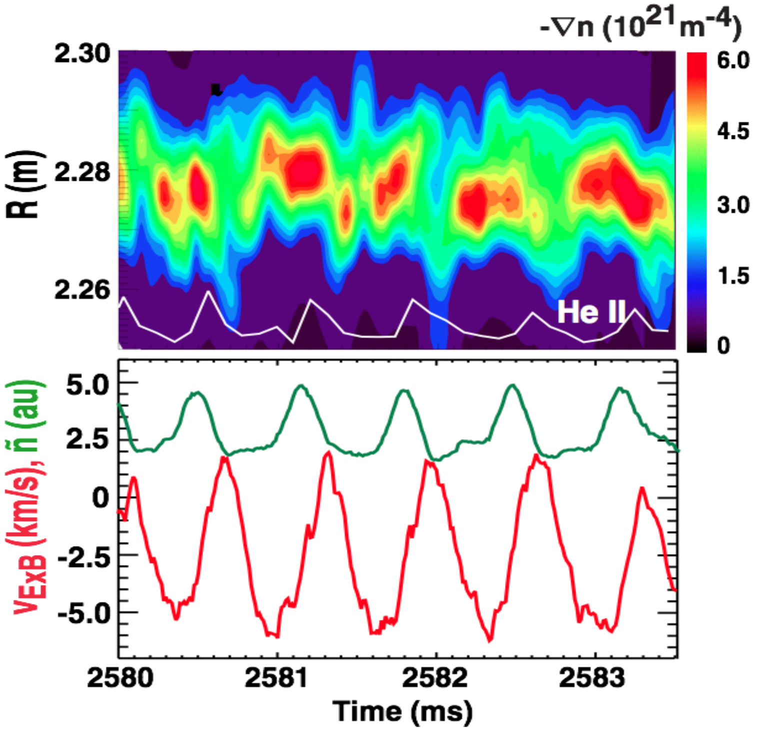

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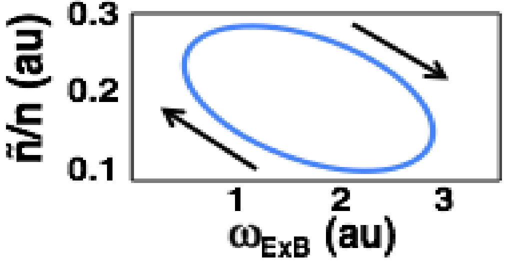
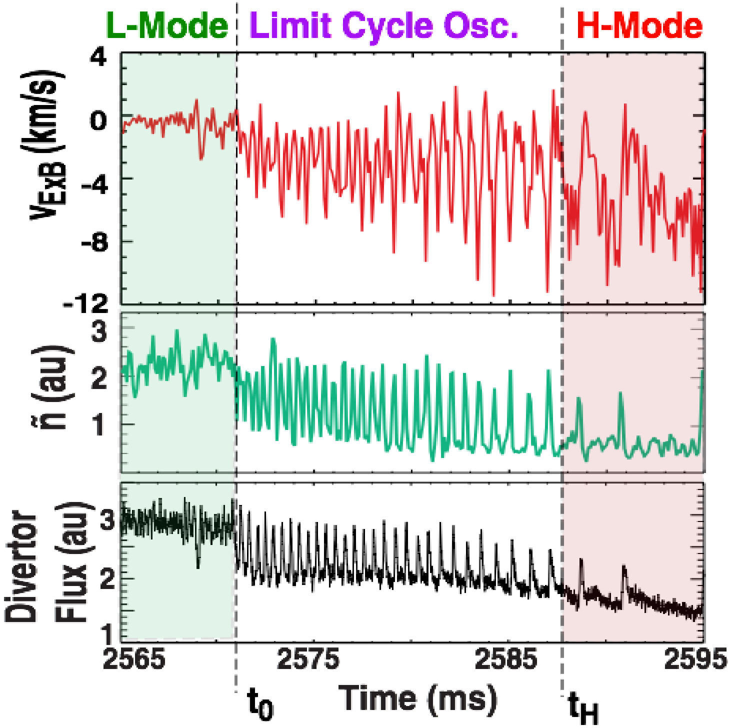
Predicting the L-H Transition Power Threshold in ITER Requires a Physics-based L-H Transition Model

- **Investigate L-H transitions at marginal heating power:**
  - expanded transition timescale
  - can exhibit limit cycle oscillations (LCO)

- **E_r, E×B shear periodically modulated; edge turbulence periodically quenched:**





- **LCO can reveal the detailed turbulence-flow interaction and trigger physics**

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Outline / Summary

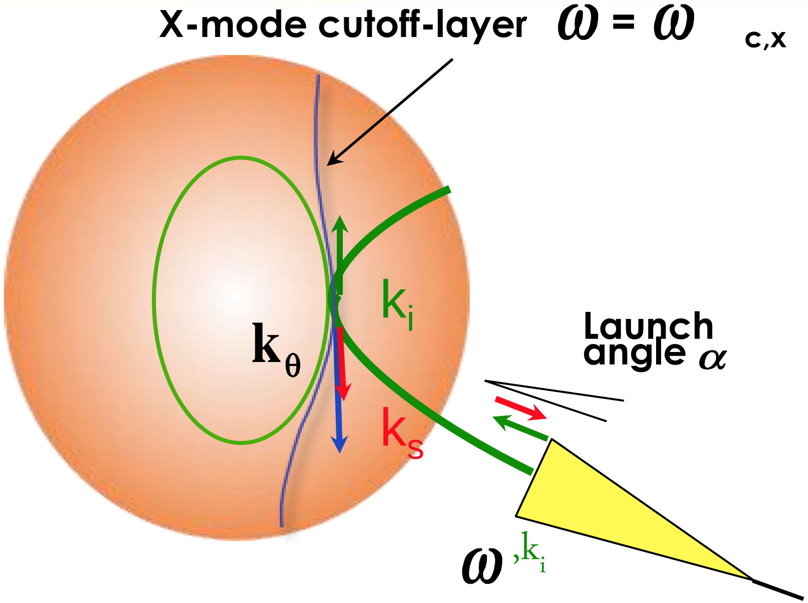
- **New:** Evidence that turbulence-driven ion flow triggers the L-Mode – LCO transition

- Causality: Turbulence-driven flow quenches turbulence initially; pressure gradient-driven flow locks in H-mode confinement

- **New:** A modified predator-prey model captures essential LCO physics

- **New:** L-mode seed flow shear at L-mode – LCO transition has a density dependence similar to the L-H power threshold

Doppler Backscattering (DBS) Measures Local Density Fluctuation Level and Turbulence Advection Velocity



Backscattering off density fluctuations with

$k_s = k_i + k_\theta$ $k_\theta = -2k_i$

Several Effects localize back-scattering to the cut-off layer

Fluctuation level vs. k_θ from back-scattered amplitude:

$\tilde{n}(k_\theta) \sim A(k_\theta)$

here: $k_\theta \sim 3.5\ \mathrm{cm}^{-1}$, $k_\theta \rho_s \sim 0.4-0.6$

E×B velocity from Doppler shift:

$$\omega_{Doppler} = v_{turb} k_\theta$$

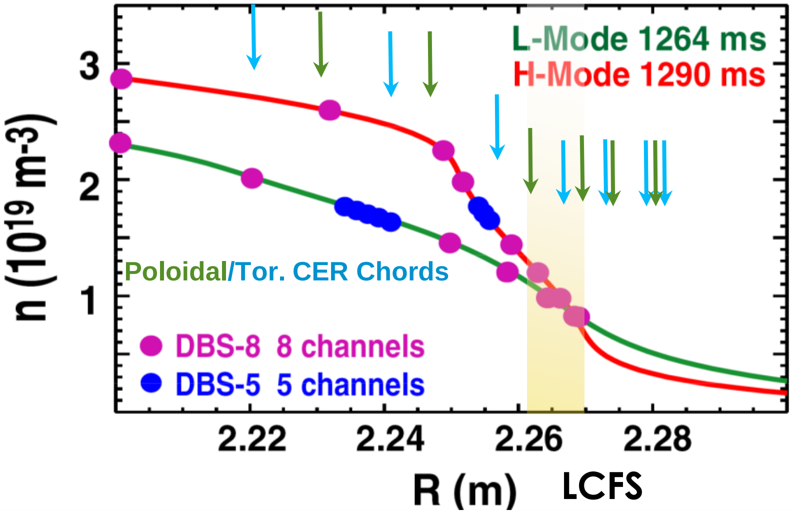
v_{turb}: Turbulence advection

Here, $v_{ph} << v_{ExB}$

$$\longrightarrow v_{ExB} \sim \omega_{Doppler} / 2k_i$$

Time Evolution and Radial LCO Structure via Multi-channel Doppler Backscattering and Main Ion CER

DBS/Main Ion CER probing locations



Density fluctuations and E × B velocity measured by DBS with high spatial/ temporal resolution

Radial mapping using density profiles from fast Profile Reflectometry (25 μs)

Main ion poloidal/toroidal flow via CER measurements

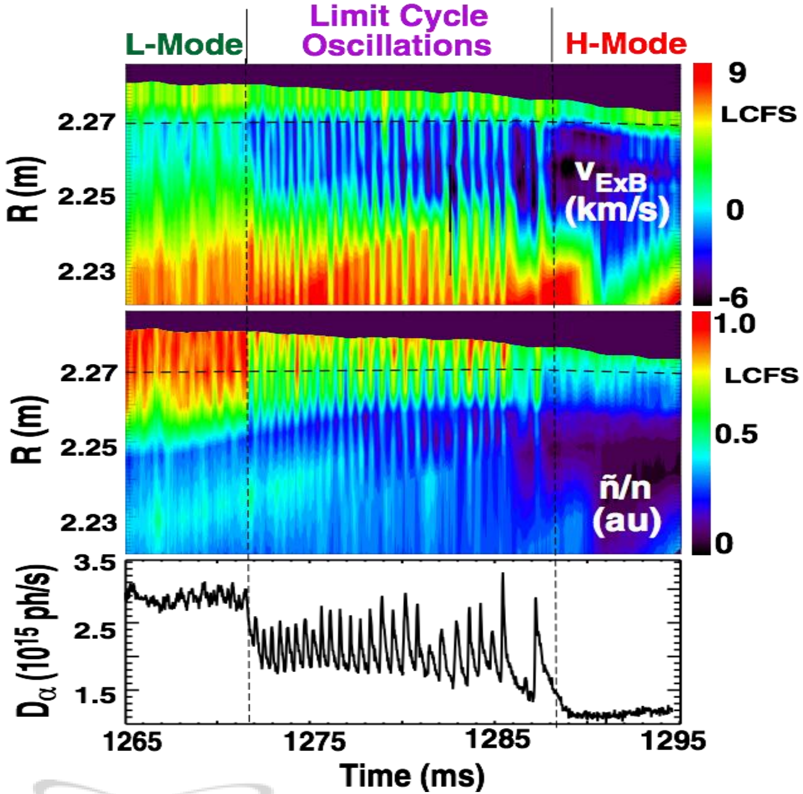
E × B flow shearing rate calculated from neighboring DBS channels:

$$\omega_{E\times B} = \frac{\mathrm{v}_{\mathrm{E\times B}}(R_2) - \mathrm{v}_{\mathrm{E\times B}}(R_1)}{R_2 - R_1}$$

Outline

Evidence of Turbulence-driven Ion Flow; Meso-scale Dipolar Flow Structure

Time Evolution and Radial LCO Structure via Multi-channel Doppler Backscattering



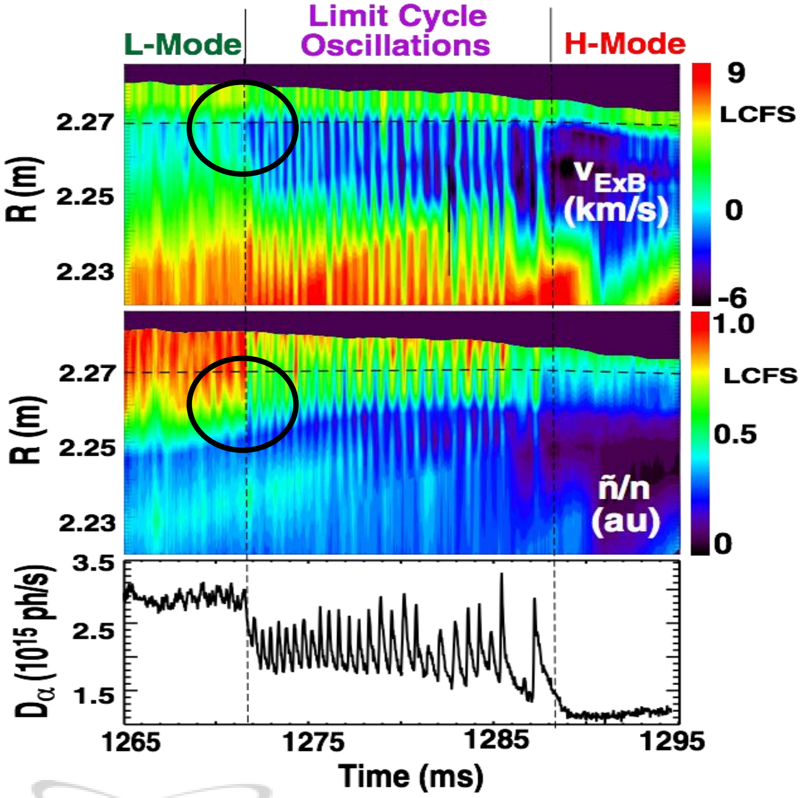
Outer Shear Layer

Inner Shear Layer

- **L-Mode:** Weak ExB shear layer turbulence peaks at/outside the separatrix
- **LCO phase:** Periodic ExB flow and turbulence suppression (starting at separatrix)
- **H-mode:** Wider and deeper shear layer; turbulence suppression maintained across the edge

Schmitz et al,
PRL 108, 2012

Time Evolution and Radial LCO Structure via Multi-channel Doppler Backscattering



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Schmitz et al,
PRL 108, 2012

How is the LCO Triggered? Obtain Turbulence-Driven Ion Flow from the Radial Ion Force Balance

$$\frac{E_r}{B} = \frac{1}{enB}\nabla p_i - \frac{v_\theta B_\phi}{B} + \frac{v_\phi B_\theta}{B}$$

from DBS

from profile
reflectometer/CER

E × B velocity measured via DBS

v × B term evaluated from radial momentum balance (subtracting ∇p_i term)

How is the LCO Triggered? Evidence for Turbulence-Driven $v_i \times B$ Flow in the Ion Diamagnetic Direction

Radial ion momentum balance:

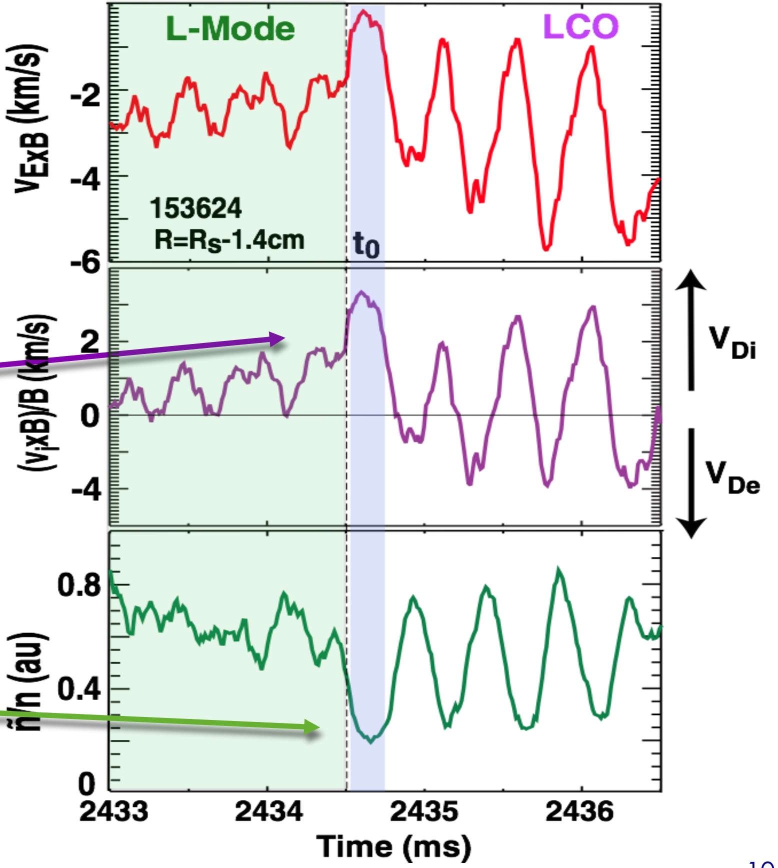
$$\frac{E_r}{B} = \frac{1}{enB}\nabla p_i - \frac{v_\theta B_\phi}{B} + \frac{v_\phi B_\theta}{B}$$

from DBS

from profile reflectometer/CER

Positive transient in $v_i \times B$ (ion diamagnetic direction) inside the LCFS at the initial turbulence quench

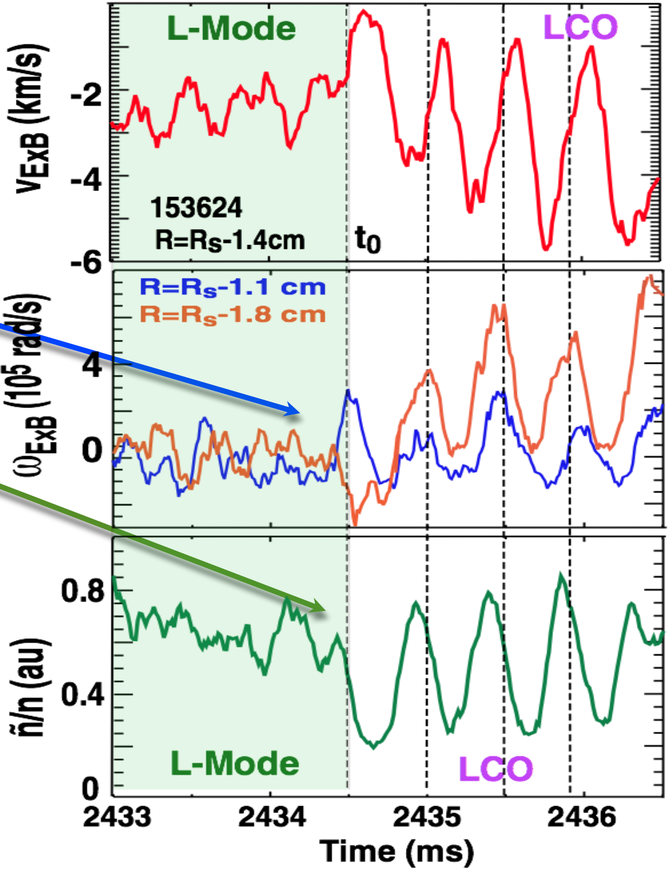
Turbulence suppressed within ~ 100 μs



Meso-scale Shear Triggers Initial Turbulence Quench

Peak negative ExB flow does not coincide with time of maximum shear (across outer shear layer)

Local meso-scale ExB shear reversal initiates first turbulence quench:



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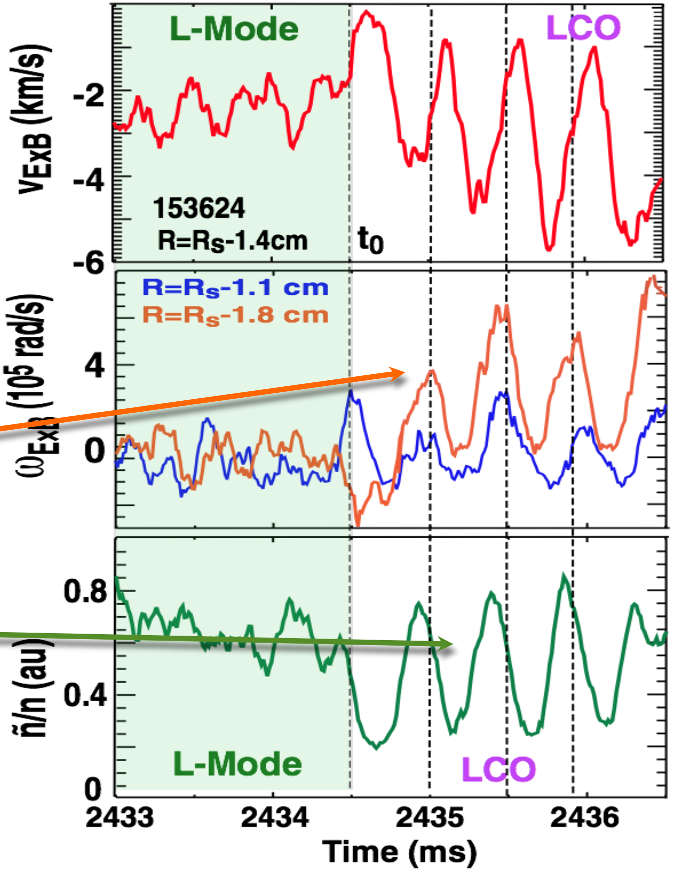
ExB Shear Across Outer Layer Increases Periodically Preceding Turbulence Suppression

Peak negative ExB flow does not coincide with time of maximum shear (across outer shear layer)

Local meso-scale ExB shear reversal initiates first turbulence quench:

ExB Shear across outer layer increases; quenches turbulence periodically during successive LCO cycles



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Turbulence Drives Main Ion Poloidal Flow

- Main ion flow (measured via main ion CER) lags ñ
- Phase delay of v_θ (~90°) is qualitatively consistent with ion flow acceleration via Reynolds stress $\langle \tilde{v}_q \tilde{v}_r \rangle$:

$$\frac{\P\langle v_q \rangle}{\P t} = -\frac{\P\langle \tilde{v}_q \tilde{v}_r \rangle}{\P r} - m\langle v_q \rangle$$

- BES velocimetry confirms (positive) Reynolds stress gradient in outer layer

He Plasma: Cross-Correlation of ñ and v_θ

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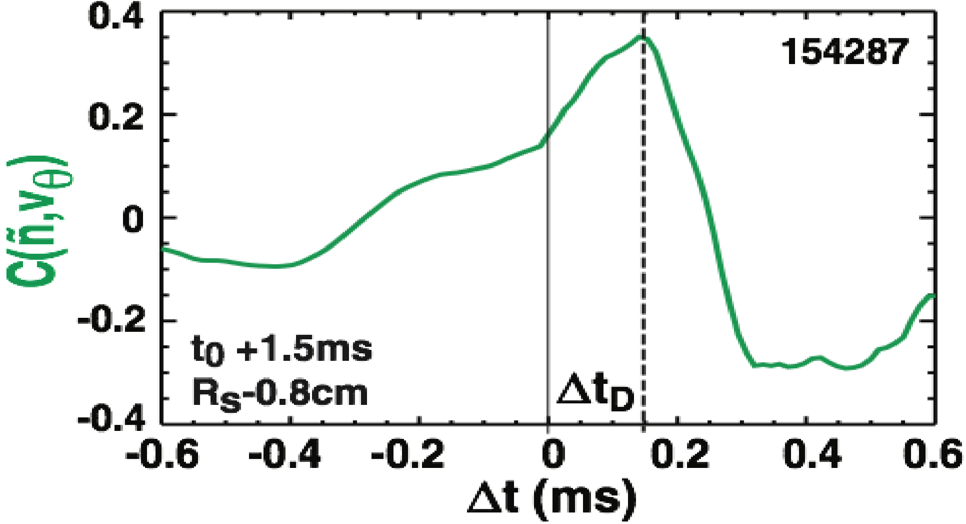


Measured early in the LCO (t_0+1.5 ms)

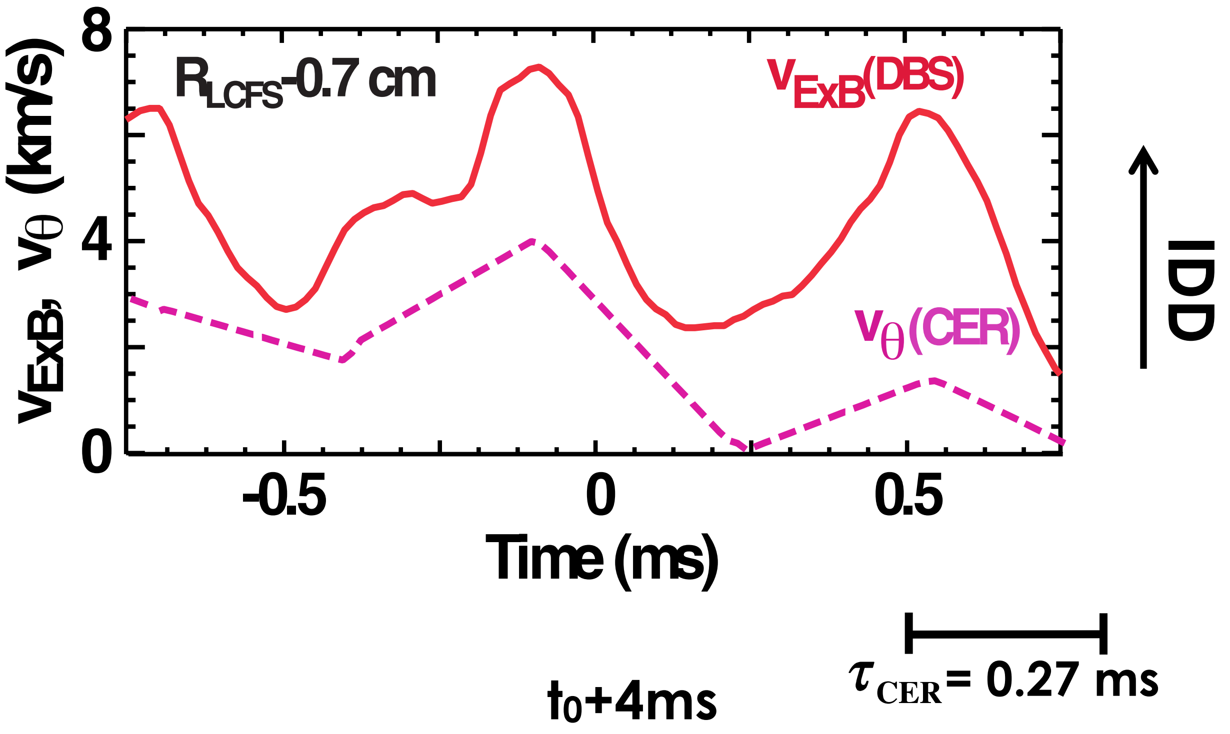
Poloidal Flow is the Main Contribution to the v_{ExB} Oscillation Early in the LCO

Phase-lock analysis:

Triangular CER waveforms due to limited CER time resolution

$v_\theta \times B$ is the dominant contribution to v_{ExB} early in the LCO

Outer Shear Layer



t_0+4ms

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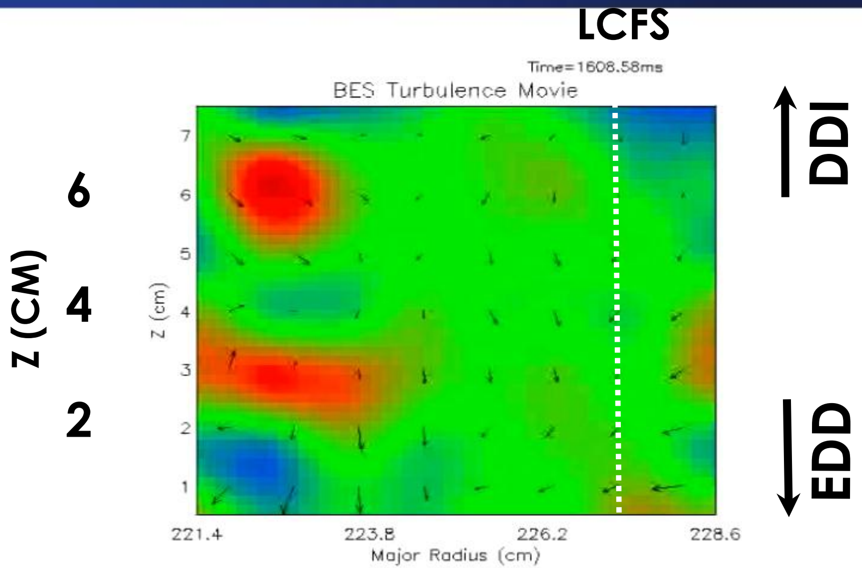
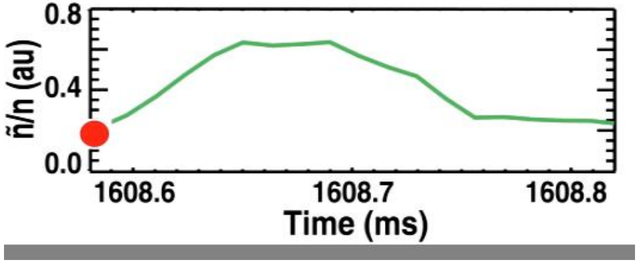
BES Shows Formation of Large Scale Eddies and Eddy Tilting/ Break-up in High Shear Regions

- **Large eddies grow at expense of smaller eddies**
- **Break-up/turbulence reduction after large eddies tilt**
- **E × B flow reversal near LCFS: IDD turbulence-driven flow at LCFS; EDD turbulence-driven flow further inboard**

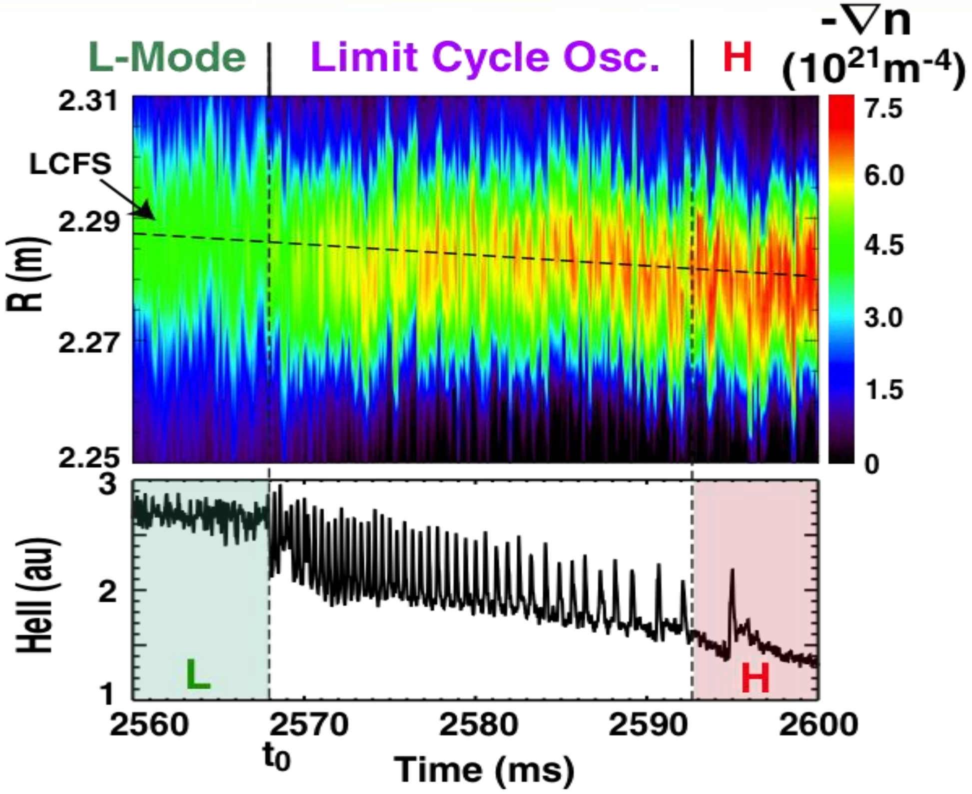




Outline

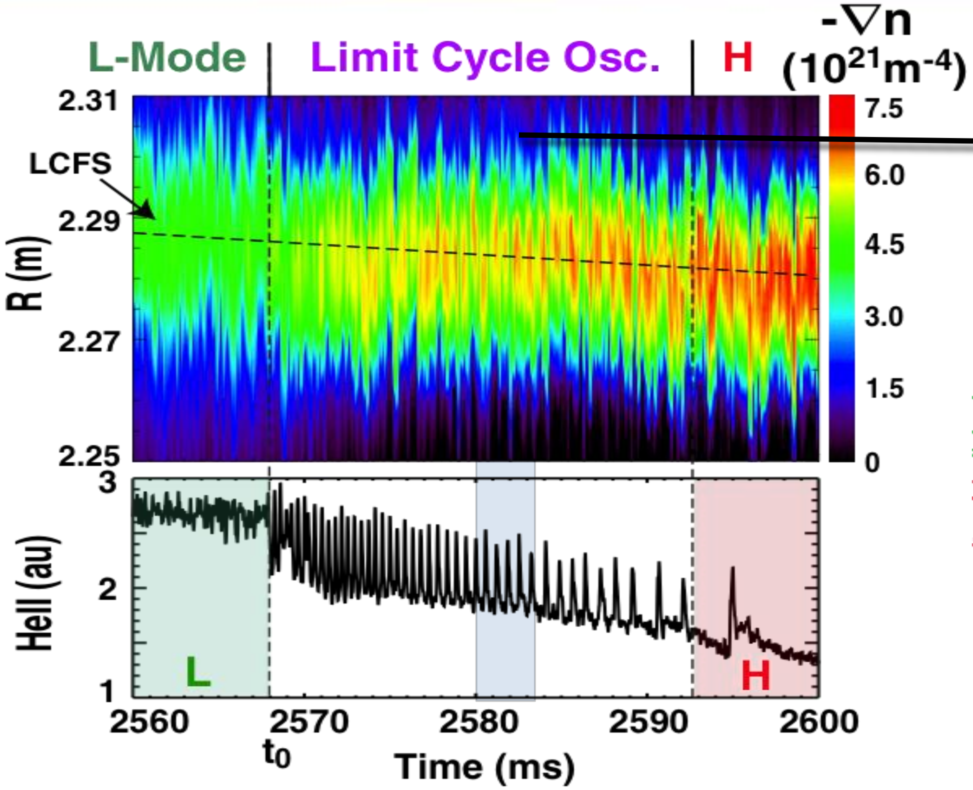
Causality of shear flow generation

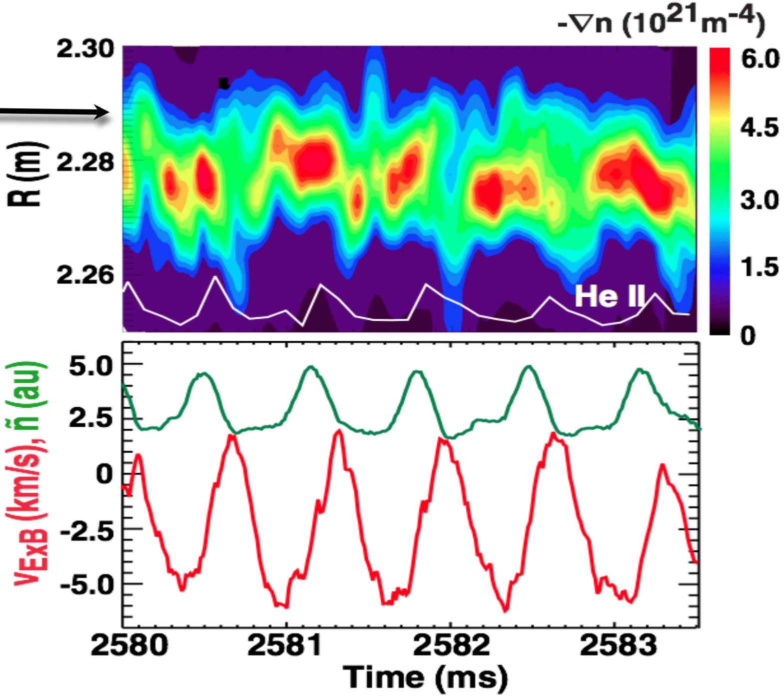
Final Transition to H-mode is due to Increasing Pressure-Gradient Driven Shear; Modulation/Increase of ∇n (∇p_i)



- ∇n is used as proxy for ∇p_i as $L_n < 0.3L_{Ti}$
- Density gradient only changes significantly well into the LCO
- Gradual increase and periodic modulation of ∇n during LCO
- Increasing ∇p slows down LCO frequency (increasing shear inhibits turbulence recovery)

Final Transition to H-mode is due to Increasing Pressure-Gradient Driven Shear; Modulation/Increase of $\nabla n, \nabla p_i$





- **Expanded time scale:**

∇n (∇p) increase after each fluctuation quench

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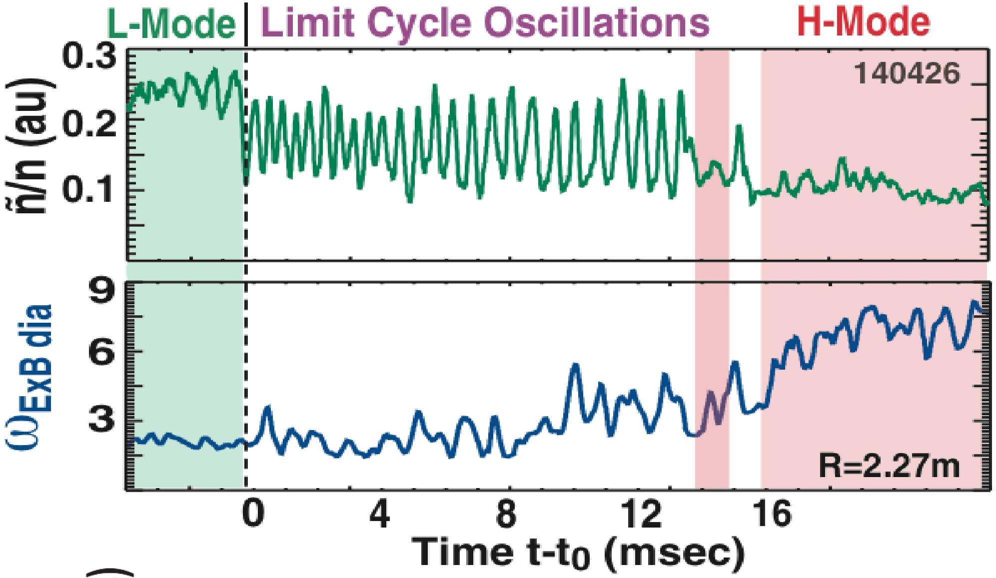
Causality of Shear Flow Generation: Turbulence-Driven Flow Shear Dominates Early in the LCO

Early in the LCO,
∇p_i lags $\omega_{E\times B}$:

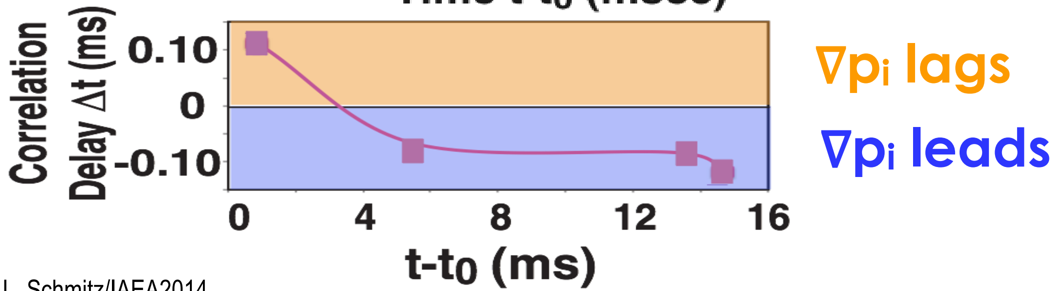
E × B Shear is not caused by the pressure gradient

Later in the LCO,
∇p_i leads $\omega_{E\times B}$:

Pressure-gradient driven shear is dominant



Correlation delay
Between $\omega_{E\times B}$ and ∇p_i



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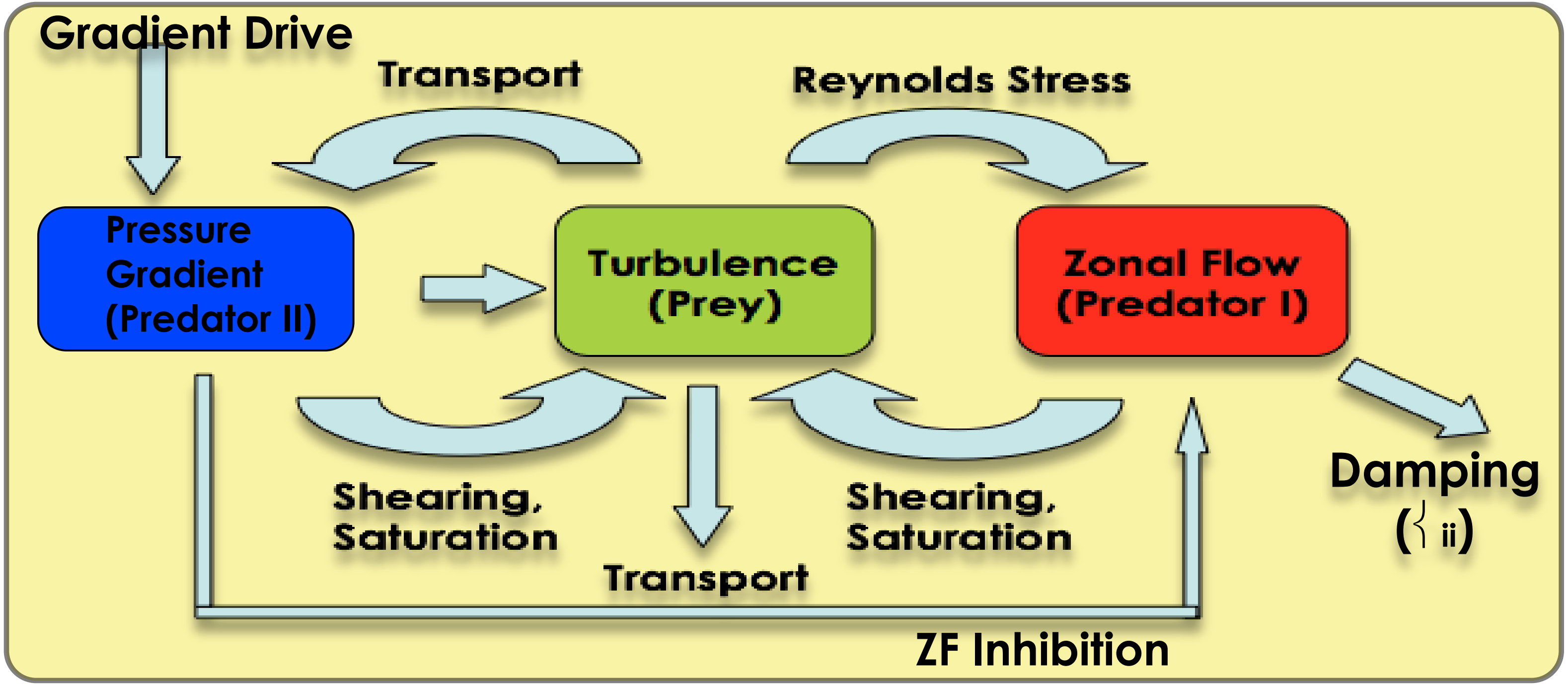
Outline

A modified Predator-prey Model Captures Essential LCO Physics

Two Coupled Feedback Cycles: Synergy of Turbulence-Driven Flow and Pressure-Gradient-Driven Flow



- Total ExB flow includes pressure-gradient-driven equilibrium flow
- Pressure gradient is modulated via the periodic change in turbulence level and transport: two interacting feedback cycles

Predator-Prey Model Predicts LCO with Opposing Turbulence-Driven and ∇p-Driven (v_{Dia}) Flow

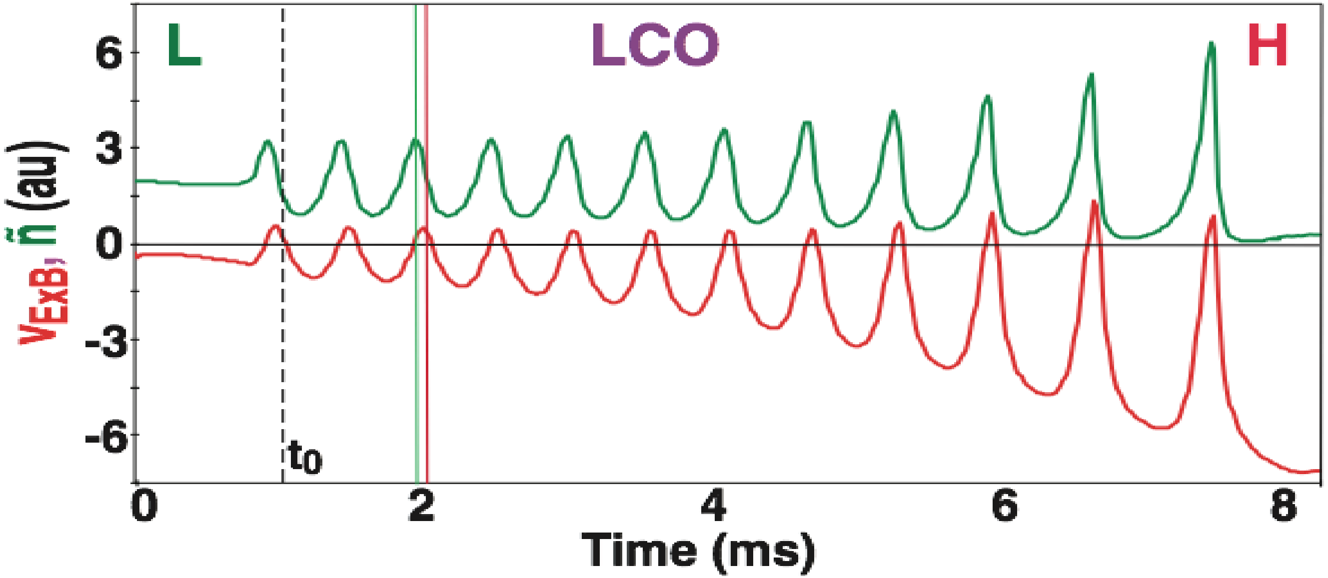
Modeling results*, including:

-neoclassical poloidal ion velocity (no toroidal flow)

-shearing by turbulence-driven and ∇p driven E×B flow

-pressure profile evolution (radial transport)

*based on Miki, Diamond, PoP 2012



Total ExB flow (includes v_θ , v_{Dia}, and turbulence-driven flow): (E_r,ñ) phasing shifts from 90° closer to 0° as diamagnetic shear becomes dominant

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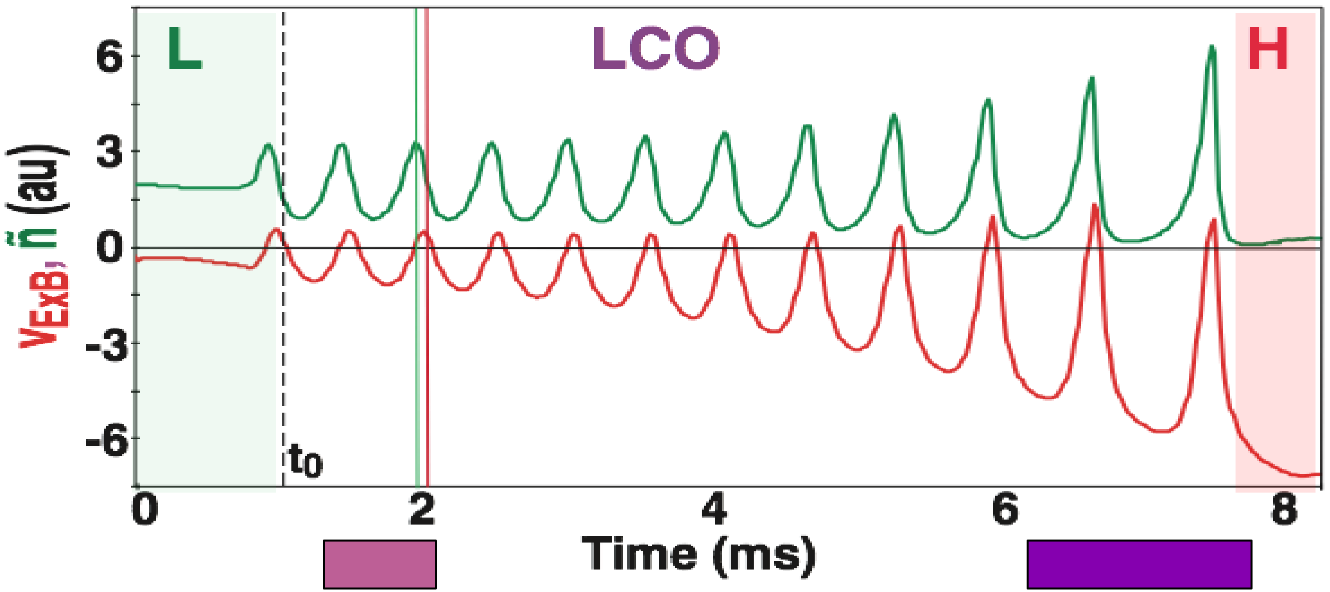

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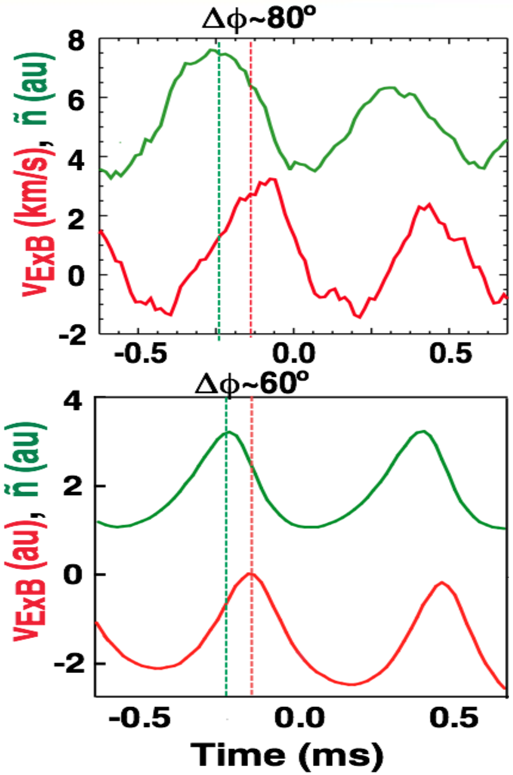
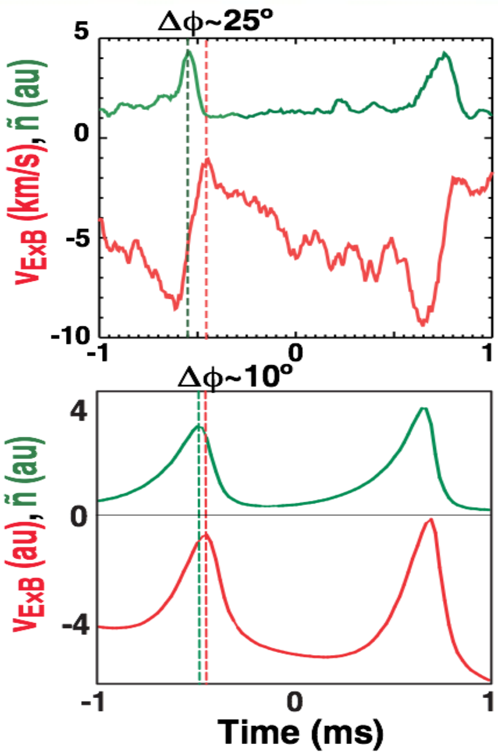
Predator-prey Model Qualitatively Reproduces the Measured Phase Shift between ñ and v_{ExB}



Early LCO
(t_0+ 1.5ms):

Experiment:
$\Delta\phi$ ~70-90°

model:
$\Delta\phi$ ~50-70°



Late LCO
(t_H-1.5ms):

Experiment:
$\Delta\phi$ ~20-30°

model:
$\Delta\phi$ ~10-20°

Quantitative differences due to variations of Zonal- and mean turbulence-driven ion flow

Outline

E × B and v × B seed flow shear at the L-mode-LCO Transition

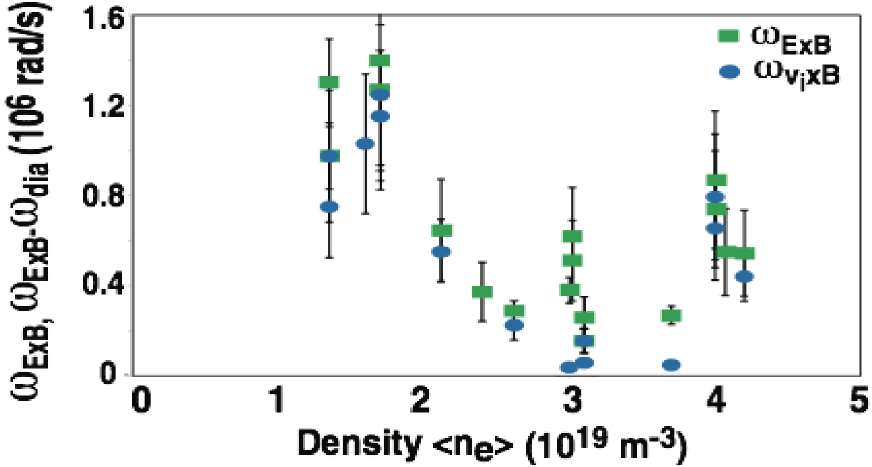
Importance of Seed Flow Shear: L-Mode E×B and v×B Flow Shear (and P_{th}) Increase at Low and High Density

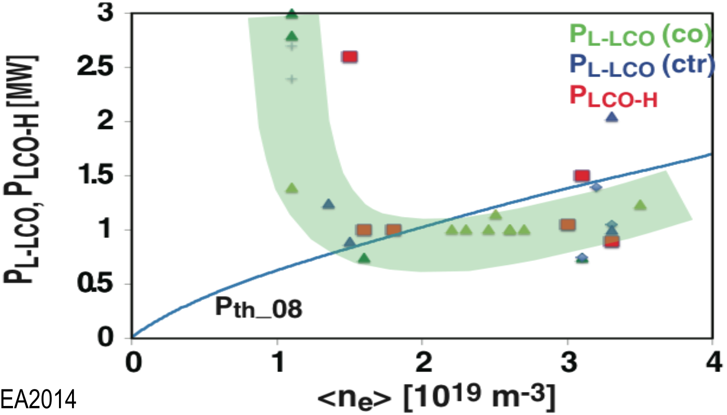
- Reynolds work P_{Re} depends on Reynolds stress and seed shear flow:

$$P_{\mathrm{Re}} = \langle \tilde{\mathbf{v}}_r \tilde{\mathbf{v}}_\theta \rangle \frac{\partial \langle \mathbf{v}_\theta \rangle}{\partial r}$$

- Total E×B shearing rate and v×B shear show a minimum at intermediate density (similar to P_{th})

- L-mode diamagnetic seed flow shearing rate ω_{Dia} does not reflect the P_{th} density dependence





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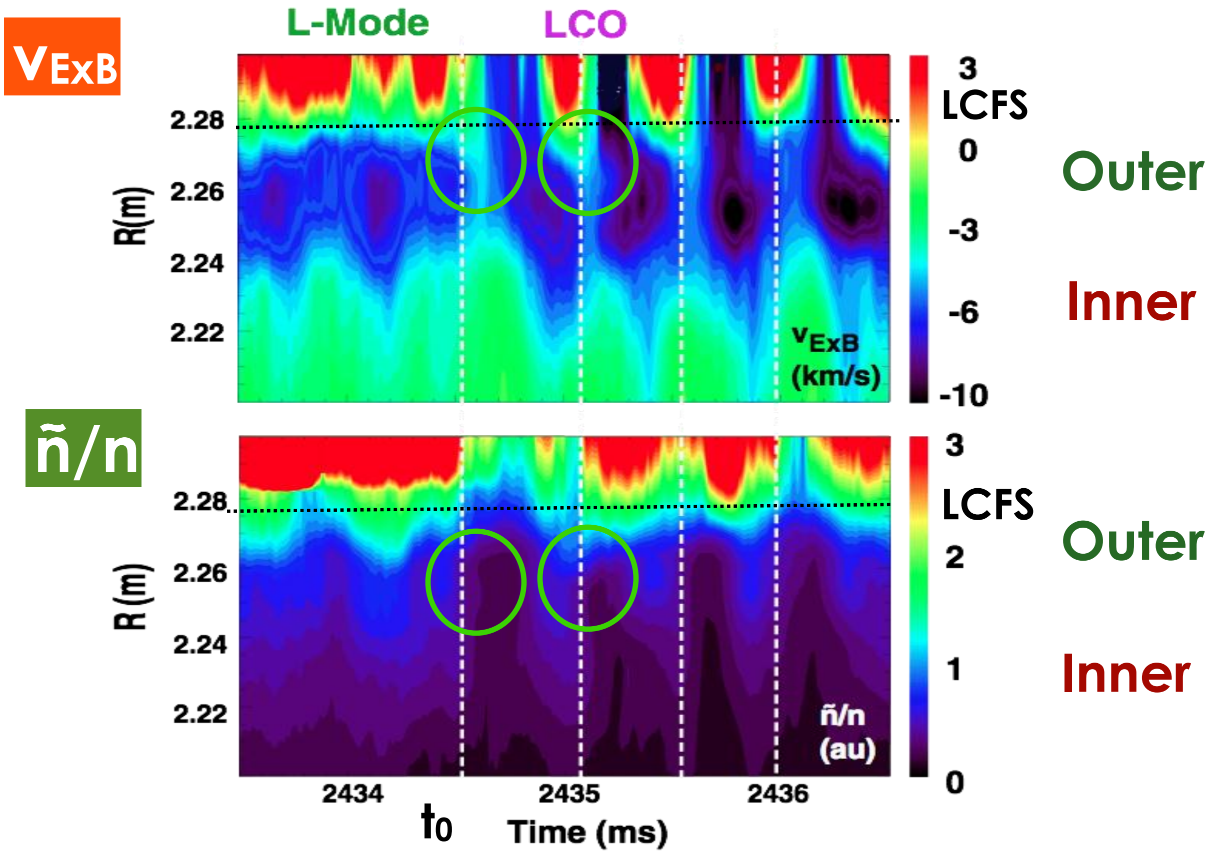
Conclusions/Physical Picture

- Strong evidence that turbulence-driven ion flow triggers LCO; evidence of dipolar meso-scale flow structure
- Causality of shear flow generation: Pressure-gradient-driven shear increases only well after the initial fluctuation quench, and locks in the final transition to H-mode
- 0-D /1-D predator-prey models captures synergy of turbulence-driven and pressure-gradient driven flow and reproduces essential experimental LCO properties
- Connection to power threshold: Both total E × B shear and v × B velocity shear increase at very low and at high plasma density (qualitatively similar to P_{th} scaling)

Positive Flow Transients in Outer Shear Layer Suppress ñ

- E × B Shearing rates peak in the outer shear layer where turbulence level is high

- Positive flow transients suppress turbulence



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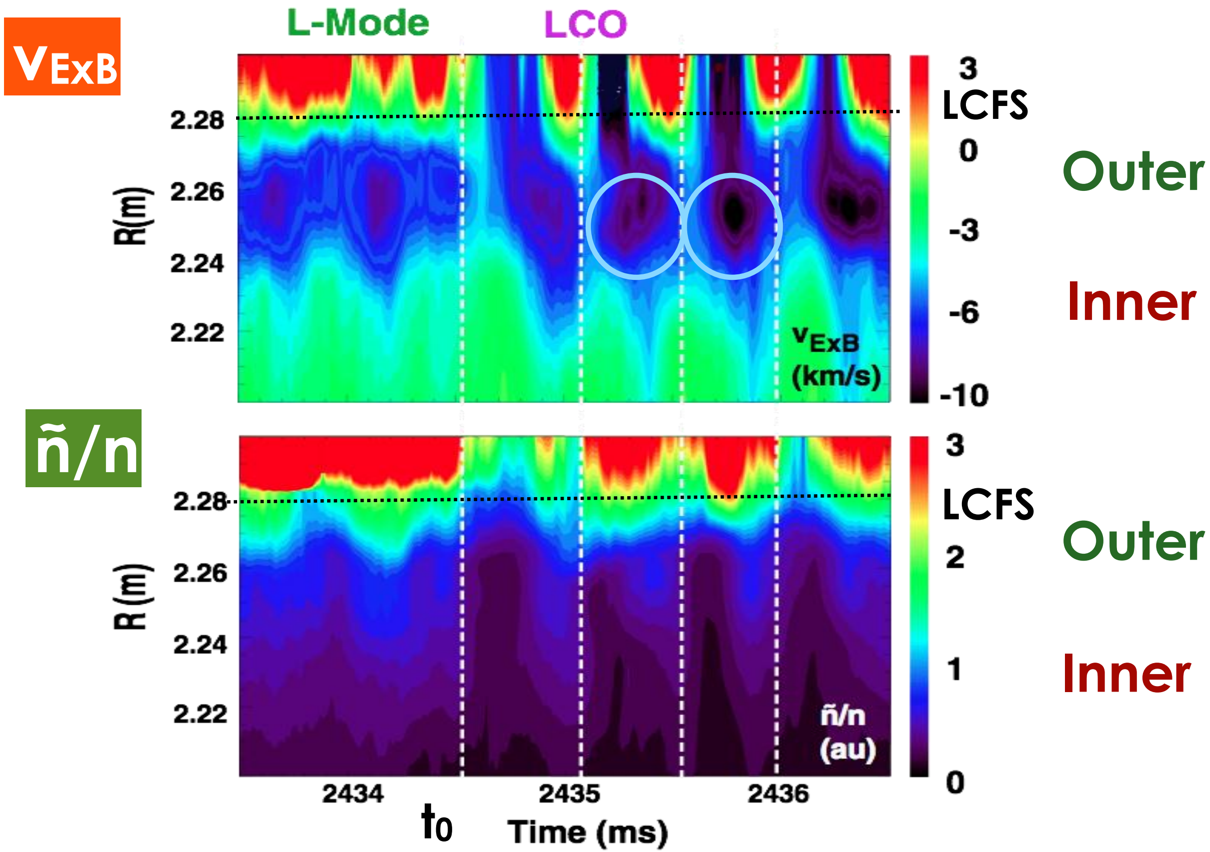
Negative Flow Transients Occur after Turbulence Suppression

- **Negative E × B transients reflect turbulent-driven flow early in the LCO**
- **Pressure-gradient-driven flow only changes significantly well into the LCO**



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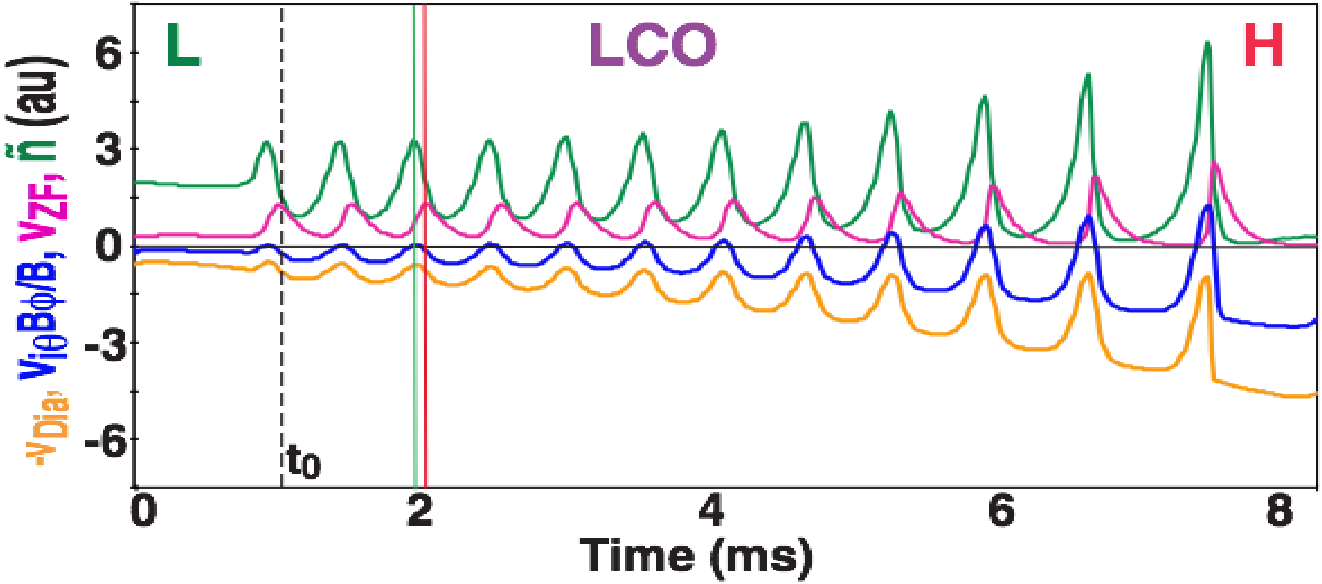
Predator-Prey Model Predicts LCO with Opposing Turbulence-Driven and ∇p-driven (v_{Dia}) Flow

0-D Predator-Prey modeling results*, including:

-neoclassical poloidal ion velocity (no toroidal flow)

-shearing by turbulence-driven and mean flows

-pressure profile evolution
-radial transport



Turbulence-drivenZonal flow v_{ZF} lags density fluctuation level ñ by 90°
Equilibrium flow is out of phase (180°) with ñ
(both consistent with observed limit cycle phasing)

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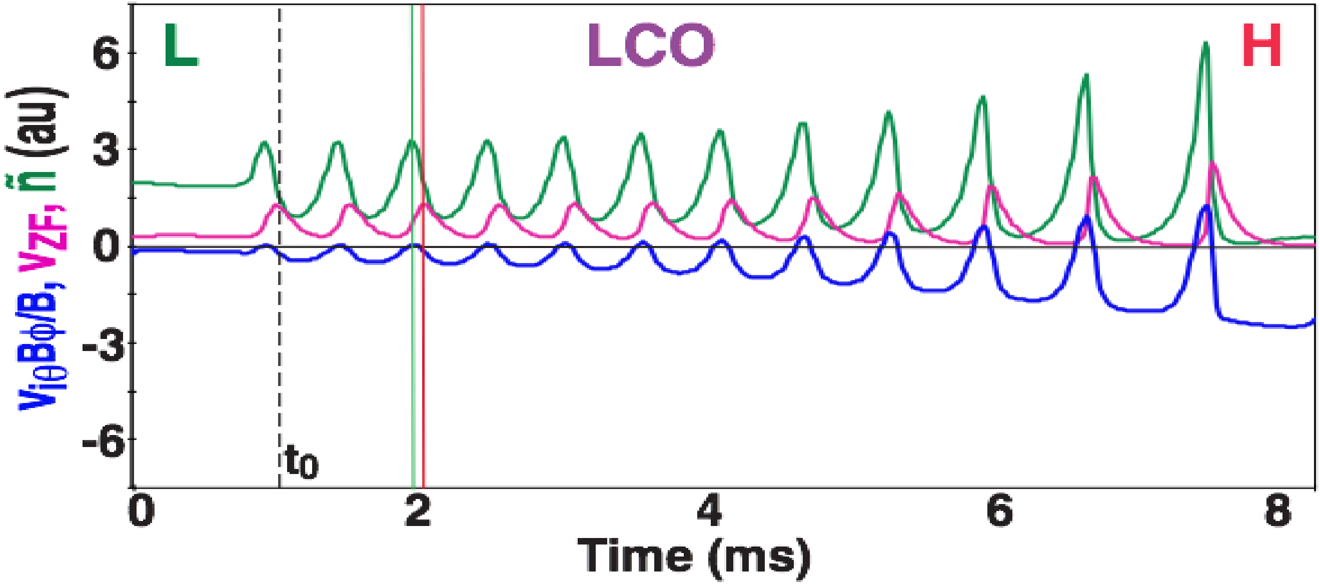

Turbulence-driven flow v_{ZF} lags ñ by 90° (qualitatively consistent with experiment

Poloidal Ion Flow lags ñ by 10-30°

consistent with observed limit cycle phasing)

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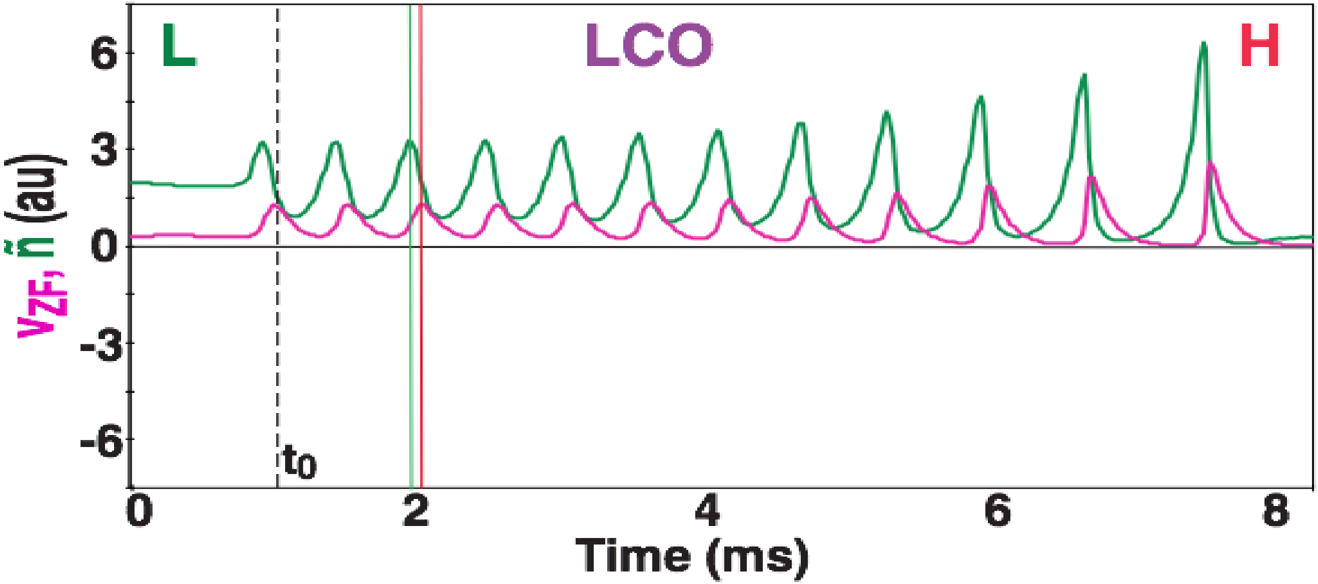


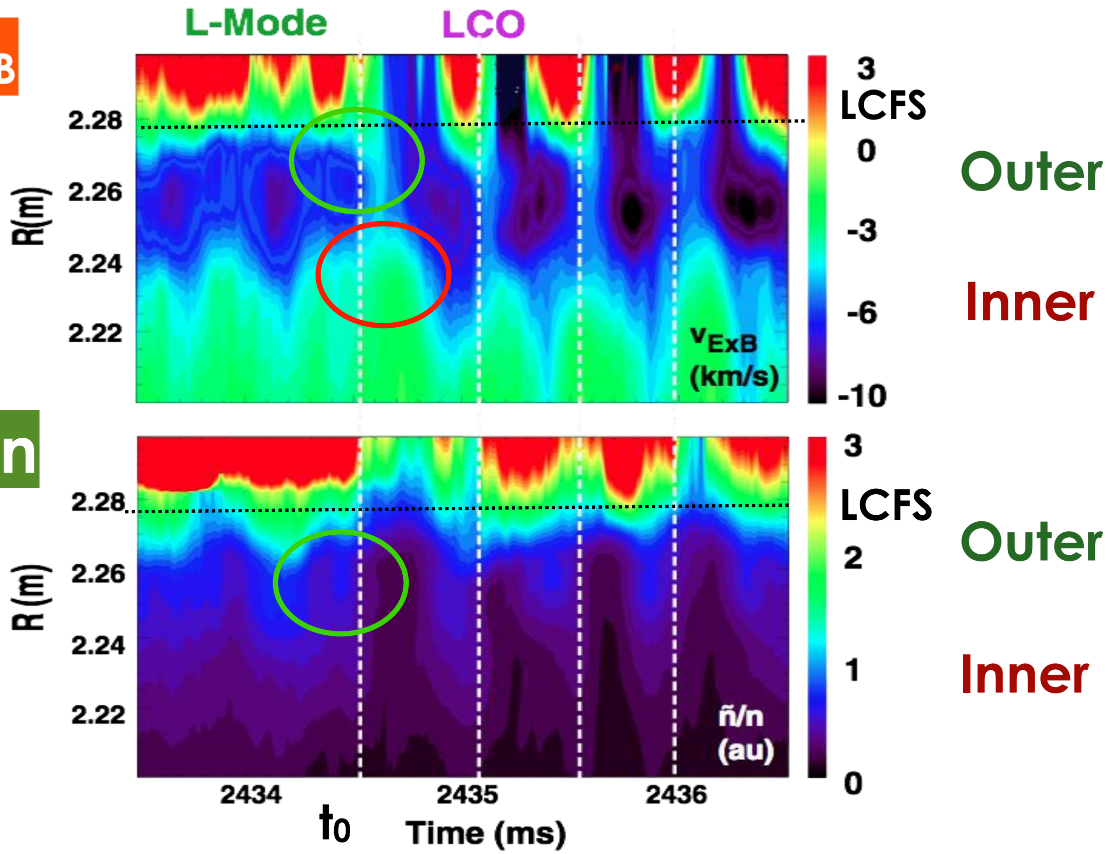
Turbulence-driven flow v_{ZF} lags density fluctuation level $\tilde{n}$ by 90° (consistent with observed limit cycle phasing)

Flow Layer Propagates Radially Inwards

- Positive transients in inner shear layer delayed;
- Consistent with radial inward propagation of LCO E × B flow*
- Mesoscale radial structure:
  $\rangle_i < L_{ExB} < L_p$

v_{ExB}

ñ/n



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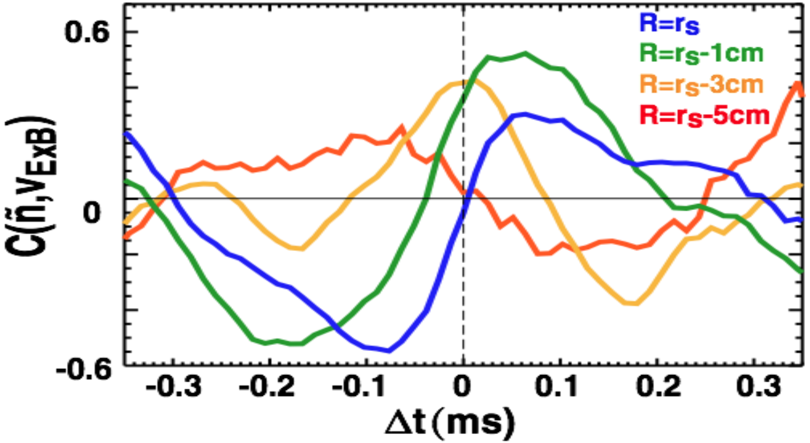
*L. Schmitz et al., PRL 2012

Limit Cycle Directions ($\tilde{n}$,v_{ExB} Phase Relation) are Consistent with Meso-scale Turbulence-Driven Flow

Cross Correlation of $\tilde{n}$ and $v_{E\times B}$



→ Opposite Limit cycle directions are observed in outer/inner shear layer

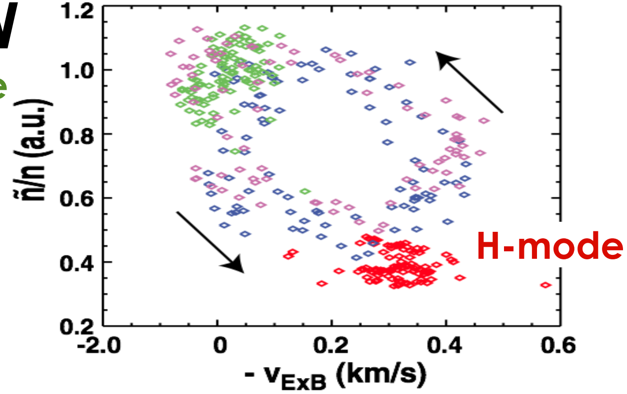
$\tilde{n}$,v_{ExB} phase relationship is consistent with observed radial E × B flow propagation

*L. Schmitz et al.,

Limit Cycle-Outer Shear Layer

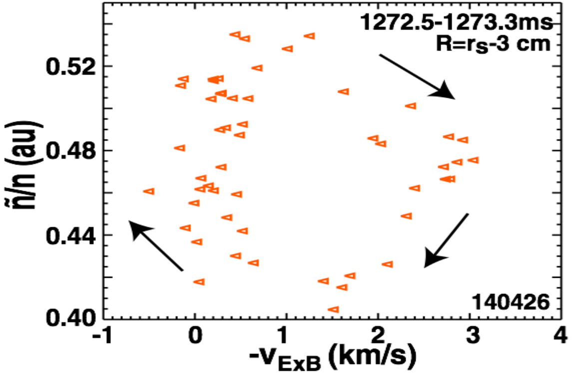
CCW

L-Mode



Limit Cycle-Inner Shear Layer

CW



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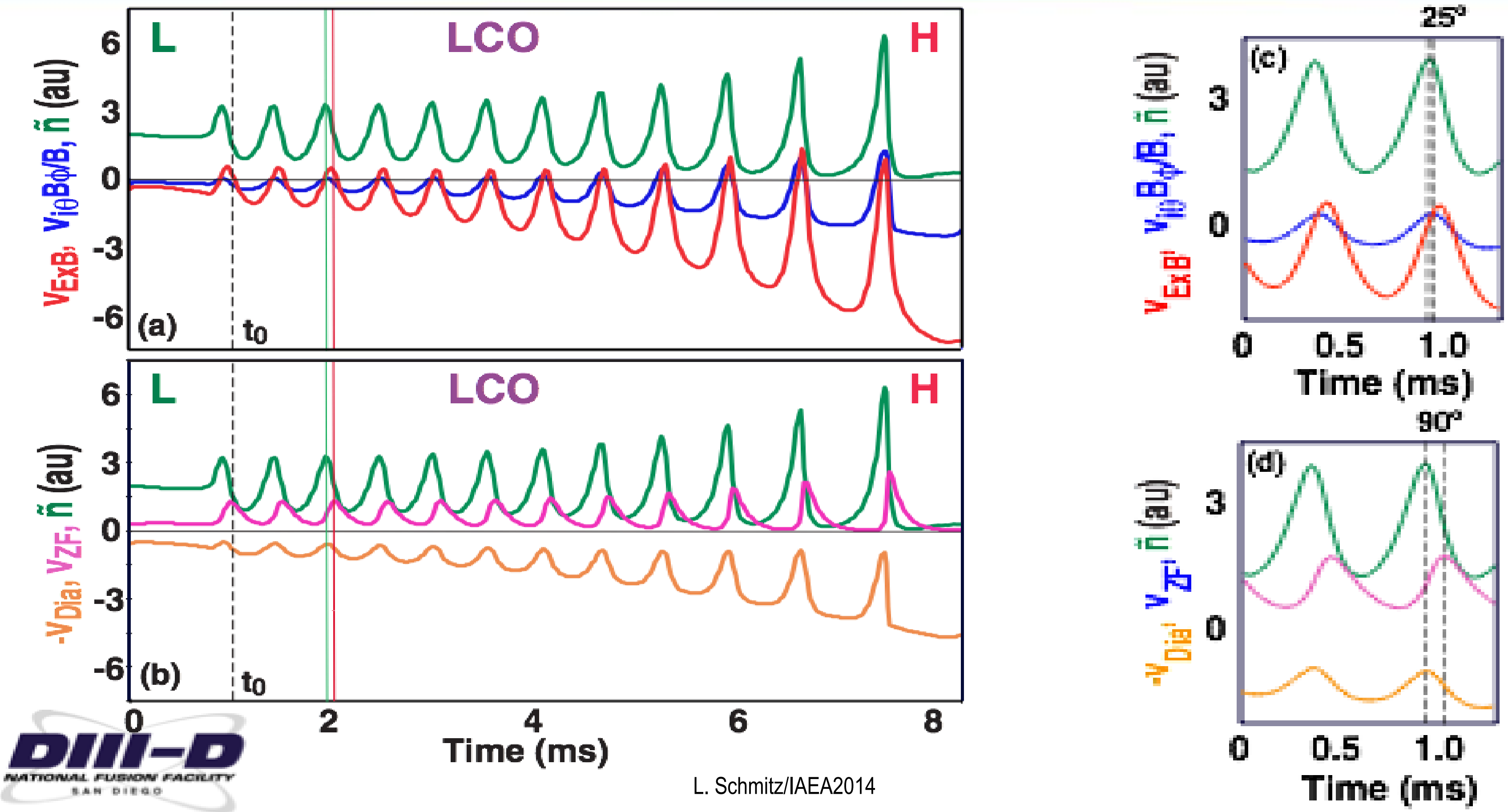

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Evidence of Turbulence-Driven Poloidal Ion Flow from Main Ion CER and DBS

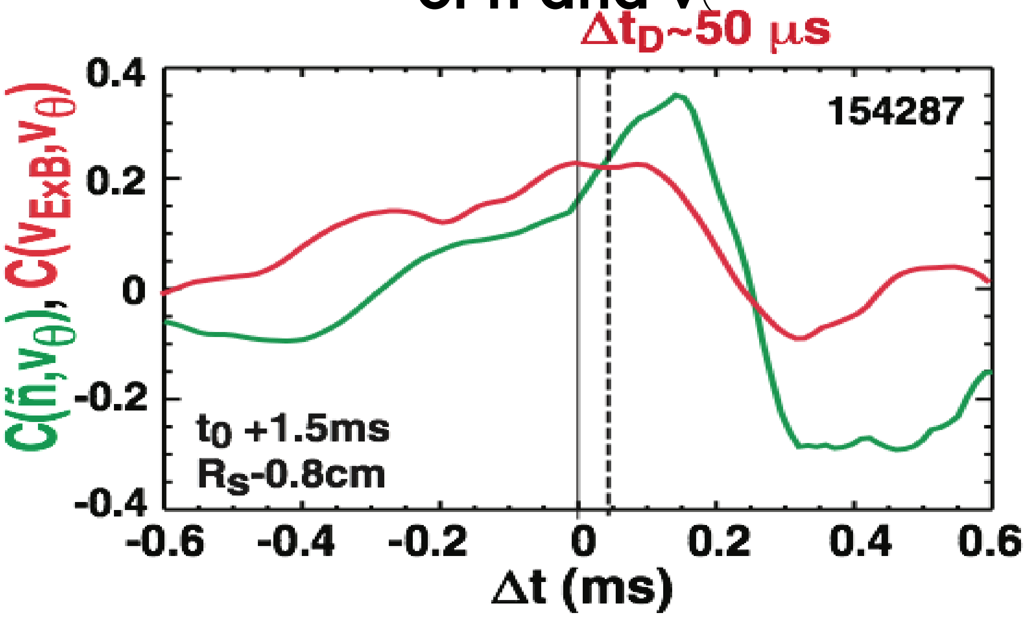
Poloidal flow acceleration via turbulence-generated Reynolds stress $\langle \tilde{v}_q \tilde{v}_r \rangle$:

$$\frac{\partial v_\theta}{\partial t} = -\frac{\partial}{\partial r}\langle \tilde{v}_\theta \tilde{v}_r \rangle - \mu \langle v_\theta \rangle$$

Main ion flow v(lags the density fluctuation level ñ

E × B velocity approximately in phase with v(:
Driven Poloidal ion flow is main contribution to $v_{E\times B}$

He Plasma: Cross-Correlation of ñ and v(



Measured early in the LCO

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SAN DIEGO

L. Schmitz/IAEA2014

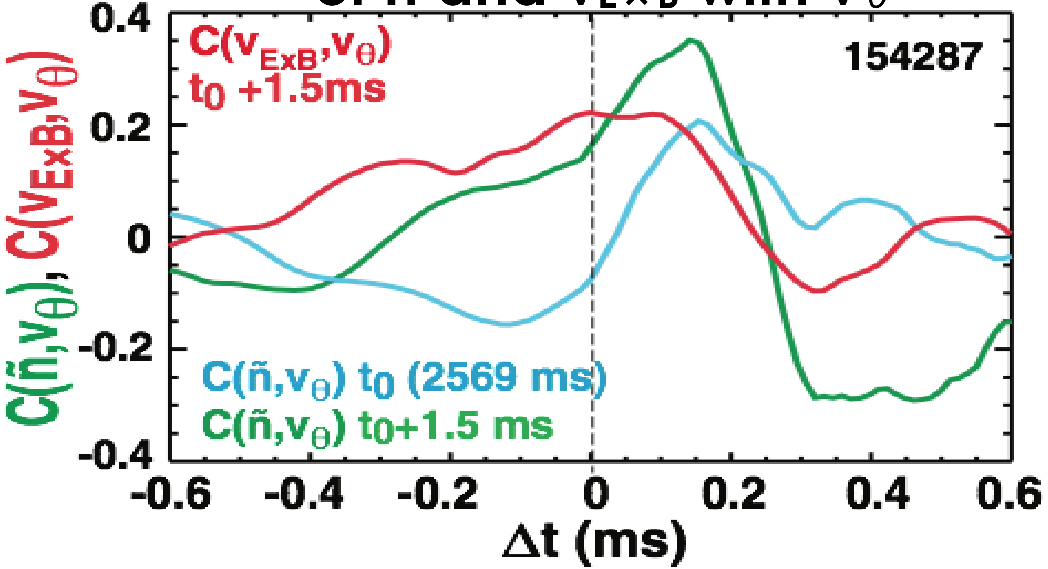
How Does the LCO Start? Compelling Evidence for Turbulence-Driven Ion Flow from Main Ion CER and DBS

Poloidal main ion flow v_θ (blue, green) lags the density fluctuation level ñ

The E × B flow is in phase with v_θ (expected if the E_r modulation results from v_θ)

Less clear correlation of ñ with toroidal velocity v_ϕ in the early LCO

He Plasma: Cross-Correlation of ñ and $v_{E\times B}$ with v_θ



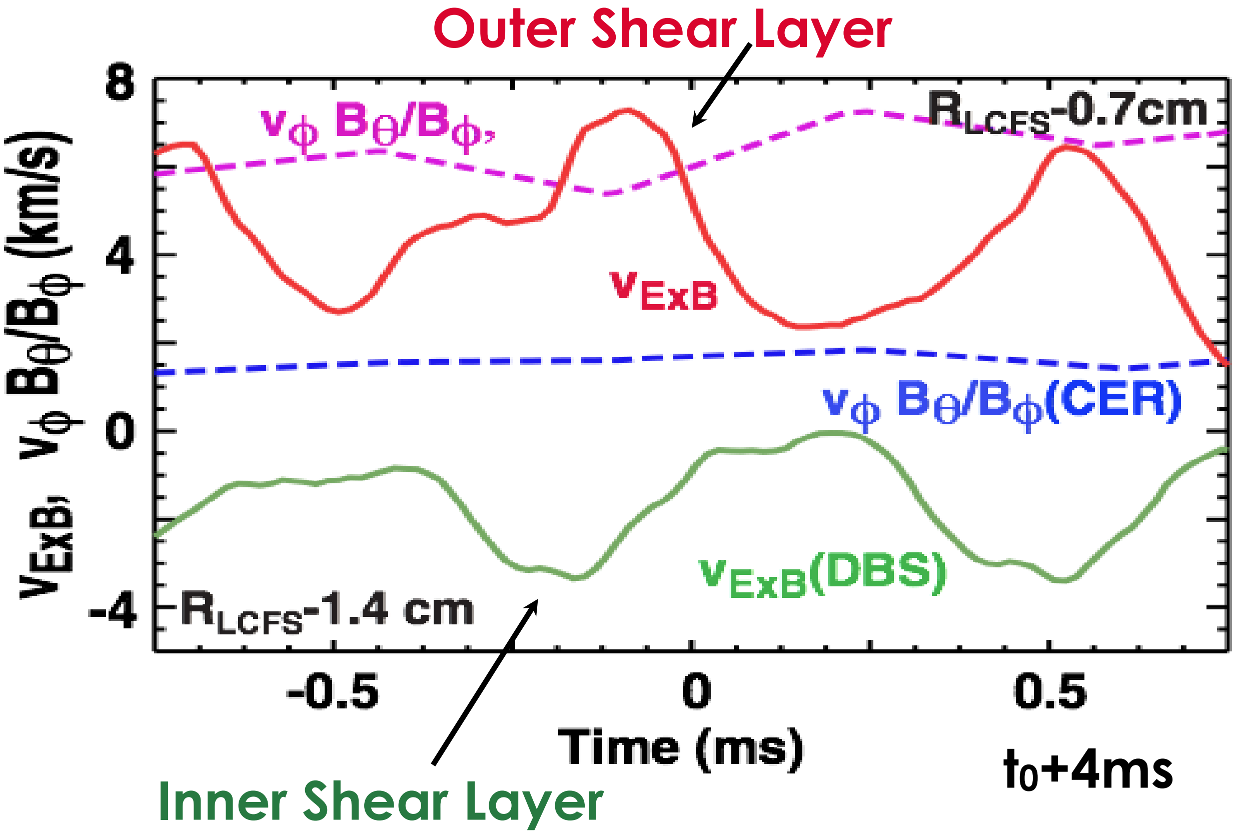
$R=R_s$-0.8 cm

Toroidal Flow Modulation is Out of Phase with ExB Velocity in Outer Shear Layer

Toroidal velocity is positive (co-current); increases locally towards LCFS (orbit-loss effect?)

Shown is the electric field component due to v)

Weak toroidal velocity modulation observed in Inner Shear Layer



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Predator-Prey Equations (1-D), Pressure Gradient (1-D) + Transport Model*,

Miki-Diamond Model* (1-D, coupled with radial transport model)

$$\frac{\partial}{\partial t}\tilde{I} = \gamma\tilde{I} - c_1\tilde{I}^2 - \alpha_0 E_0 - \alpha_V E_V$$

Turbulence Evolution

$$\frac{\partial}{\partial t}E_0 = \frac{\alpha_0 E_0 \tilde{I}}{1+\zeta_0 E_V} - \gamma_{damp}E_0$$

Turbulence-driven shear flow energy

$$\frac{\partial}{\partial t}P_i^{'} = Q - c_2\tilde{I}P_i^{'} - c_3\tilde{I}$$

Pressure gradient evolution

$$\frac{\partial}{\partial r}\langle V_E\rangle = -\frac{1}{eB}\frac{\partial}{\partial r}\left[\frac{1}{n}\frac{\partial P_i}{\partial r}\right] - c_4\frac{\partial}{\partial r}\langle \mathrm{v}_\theta\rangle$$

Mean Shear Flow

$$\frac{\partial}{\partial t}\langle \mathrm{v}_\theta\rangle = -\frac{\partial}{\partial r}\langle \tilde{\mathrm{v}}_r\tilde{\mathrm{v}}_\theta\rangle - \mu_0\nu_{ii}q^2R^2\left(\langle \mathrm{v}_\theta\rangle - 1.17\frac{\rho_i}{L_T}\right)$$

Mean poloidal flow (Reynolds stress + neoclassical flow)

*Miki and Diamond, PoP 2012)

Motivation

- **The presently used empirical L-H power threshold scaling does not reflect important parameters, or the observed non-monotonic dependency of P_{th} on density:**

$$P_{\mathrm{th}}(\mathrm{MW}) = 0.049 B_{\Phi}^{0.8} n_{\mathrm{e}}^{0.72} S^{0.94}$$ **(2008 multi-machine scaling)**

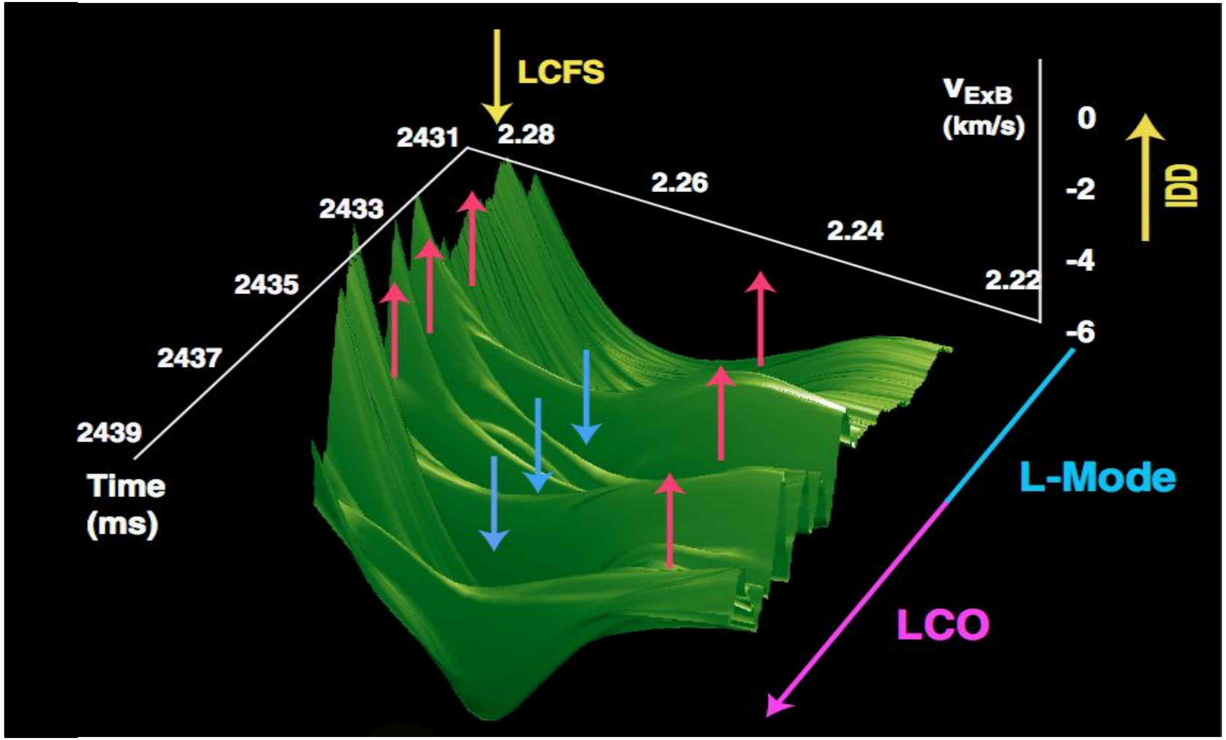
- **Predicting the L-H transition power threshold in ITER requires a physics-based L-H transition model:**

- Link trigger physics/microscopic flow/turbulence dynamics to the macroscopic power threshold scaling
- Extract critical seed shear flow/ critical turbulence-driven shear flow and determine their role in the P_{th} scaling

Meso-Scale Dipole Structure of Turbulence-Driven Flow: Alternating Transients in Outer / Inner Shear Layer

E × B Shearing rates peak in the outer shear layer (pos. flow: magenta arrows) where turbulence level is high

Radial profile consistent with radial inward propagation of LCO E × B flow*



Outer Shear Layer

Inner Shear Layer

*L. Schmitz et al., PRL 2012