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

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Summary

- New measurements reveal key role that \textit{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?
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:

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

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

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]

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

\[ P_{LF}^{diss} = V_{LF} V_{E}^{2LF} \]

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

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

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

\[ \gamma_{pl}^{\text{corr}} = \gamma_{lab}^{\text{corr}} - V_{\text{ExB}} / L_{\theta}^{\text{corr}} \]

\[ \langle \tilde{V}_{\perp}^2 \rangle \]

\[ \langle \tilde{V}_r \tilde{V}_\theta \rangle \]

$V_{\text{ExB}}^{LF}$ includes $f_f^{<f_c^{m,n=0}} \sim 5 \text{kHz}$

assuming that $\tilde{V}=\frac{-\nabla \phi_{fl} \times B}{B^2}$

Complement w/ BES, DBS, …

Fluctuation diagnostics

Experiments show that this actually occurs

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

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

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

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

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

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

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

[Manz, PoP12]
HL2A: ECH L-mode Plasmas
Strength of $m,n=0$ ExB Shear Flow Drive Increases with $P_{aux}$ inside the LCFS

Ref: M. Xu, PRL’12

What happens with further increases of heating power?

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

- 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 $m,n=0 \text{ ExB}$ is **Driven by Turbulent Stress**

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

![Graph showing periodic maxima and ExB acceleration onset](image-url)
m,n=0 ExB Flow Becomes **Dominant Turbulent Power Loss Channel** in LCO Regime

- 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. $P_{\text{LF}}/v^2$ value exceeds L-mode energy input rate & rapidly drains turbulent energy

DIII-D: LCO TO H-mode Transition
Grad-$P_i$ component of ExB grows as LCO progresses

Ref: L. Schmitz, PRL ‘12

- Total $\omega_{\text{ExB}}$ larger than grad-$P_i$ component, $\omega_{\text{ExB dia}}$ early in LCO
- $\omega_{\text{ExB dia}}$ 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

- 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 \(\gamma_{ef}\)
EAST: L-H Transition Studies
Power transfer to \( m,n=0 \) ExB plays key role in L-H transition

Turbulence Collapses when:

\[ P_{LF} > P_{in} - P_{HF} \]

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

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

\[ \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle V_{ZF}^{'} \approx \left( \gamma_{eff} - \gamma_{decorr} \right) \tilde{v}_{\perp}^2 \]
Comparison to Predator-Prey Model
Predator-Prey Reduced Model

POWER BALANCE MODEL

\[ \frac{\partial \tilde{v}^2}{\partial t} = \gamma_{\text{eff}} \tilde{v}^2 - \gamma_{\text{decorr}} \tilde{v}^2 - \langle \tilde{v}_r \tilde{v}_\theta \rangle' V_{ExB}^{LF} \]

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

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

\[ \langle \tilde{v}_r \tilde{v}_\theta \rangle \propto \frac{\bar{V}_{ExB}^{LF'}}{1 + \alpha \bar{V}_E^2} \]

\[ q \propto -\langle \tilde{v}_r^2 \rangle \tau_{\text{corr}} \nabla p_i \]

\[ \bar{V}_{ExB}^' \propto \nabla p_i \]

\[ \gamma_{\text{eff}} = \gamma_{\text{eff}} (\nabla n, \nabla T, \bar{V}_E) \]
Slow Power Ramp Gave an LCO State Leading to H-mode….

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

Kim & Diamond, PRL’03
Predator-Prey Model Reproduces Observed L-H Transition Dynamics

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

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

- In L-mode Rate of Power Transfer from Turbulence into \( m,n=0 \) ExB Flow Increases with \( P_{aux} \)
- 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
- \( \text{grad}-P_{ion} \) 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

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 \(~2\text{-}3\text{cm}\) inside LCFS

ref: Schmitz PRL’12
Probe & BES Velocimetry Give Similar Results

Probe Results

BES Results
PRELIMINARY
Z. Yan & G. McKee, Private Comm.

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

![Diagram]

Force balance
On fluid element:

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

Turbulent momentum conservation eqn:

\[ \frac{\partial \langle V \rangle}{\partial t} = -\nabla \cdot \tilde{\Pi}_t - \nu \langle V \rangle + \ldots \]

\[ \tilde{\Pi}_t = \langle \tilde{v}\tilde{v} \rangle - \frac{\langle \tilde{b}\tilde{b} \rangle}{mn\mu_0} \]

Divergence of Turbulent Stress Can Amplify Flow!