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

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

$E_r$, $E\times B$ shear periodically modulated; edge turbulence periodically quenched:

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

Fluctuation level vs. $k_θ$ from back-scattered amplitude:

$\bar{n}(k_θ) \sim A(k_θ)$

here: $k_θ \sim 3.5 \text{ cm}^{-1}$, $k_θ\rho_s \sim 0.4-0.6$

ExB velocity from Doppler shift:

$\omega \quad \text{Doppler} = v_{\text{turb}}$  

$v_{\text{turb}}$: Turbulence advection

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

$\Rightarrow \quad v_{\text{ExB}} \sim \omega_{\text{Doppler}}/2k_i$
Density fluctuations and $E \times B$ velocity measured by DBS with high spatial/temporal resolution

Radial mapping using density profiles from fast Profile Reflectometry (25 $\mu$s)

Main ion poloidal/toroidal flow via CER measurements

$E \times B$ flow shearing rate calculated from neighboring DBS channels:

$$\omega_{E \times B} = \frac{v_{E \times B}(R_2) - v_{E \times B}(R_1)}{R_2 - R_1}$$
Evidence of Turbulence-driven Ion Flow; Meso-scale Dipolar Flow Structure
Time Evolution and Radial LCO Structure via Multi-channel Doppler Backscattering

- **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

L. Schmitz/IAEA2014
How is the LCO Triggered? Obtain Turbulence-Driven Ion Flow from the Radial Ion Force Balance

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

- \( E \times B \) velocity measured via DBS
- \( v \times B \) term evaluated from radial momentum balance (subtracting \( \nabla p_i \) term)
How is the LCO Triggered? Evidence for Turbulence-Driven $v_i \times B$ Flow in the Ion Diamagnetic Direction

Radial ion momentum balance:

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

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

Turbulence suppressed within $\sim 100 \mu s$
Peak negative $E \times B$ flow does not coincide with time of maximum shear (across outer shear layer).

Local meso-scale $E \times B$ shear reversal initiates first 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:

ExB Shear across outer layer increases; quenches turbulence periodically during successive LCO cycles
Turbulence Drives Main Ion Poloidal Flow

- Main ion flow (measured via main ion CER) lags $\bar{n}$

- Phase delay of $V_\theta$ ($\sim 90^\circ$) is qualitatively consistent with ion flow acceleration via Reynolds stress $\langle \tilde{v} \tilde{v}_r \rangle$:
  \[
  \frac{\langle v \rangle}{t} = \frac{\langle \tilde{v} \tilde{v}_r \rangle}{r} \langle v \rangle
  \]

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

He Plasma: Cross-Correlation of $\bar{n}$ and $V_\theta$

* $\Delta t_D \sim 0.15$ ms

* Measured early in the LCO ($t_0 + 1.5$ ms)

\[
\frac{\partial v}{\partial t} = -\frac{\partial v}{\partial r} - m v_q
\]
Poloidal Flow is the Main Contribution to the $v_{\text{ExB}}$ 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 $v_{\text{ExB}}$ early in the LCO
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

• $E \times B$ flow reversal near LCFS: IDD turbulence-driven flow at LCFS; EDD turbulence-driven flow further inboard

L. Schmitz/IAEA2014
Causality of shear flow generation
Final Transition to H-mode is due to Increasing Pressure-Gradient Driven Shear; Modulation/Increase of $\nabla n$ ($\nabla p_i$)

- $\nabla n$ is used as proxy for $\nabla p_i$ as $L_n < 0.3L_{ti}$
- Density gradient only changes significantly well into the LCO
- Gradual increase and periodic modulation of $\nabla n$ during LCO
- Increasing $\nabla p$ 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: $\nabla n (\nabla p)$ increase after each fluctuation quench
Early in the LCO, $\nabla p_i$ lags $\omega_{E \times B}$:

$E \times B$ Shear is not caused by the pressure gradient.

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

Pressure-gradient driven shear is dominant.

Correlation delay Between $\omega_{E \times B}$ and $\nabla p_i$
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 $\nabla p$-Driven ($v_{\text{Dia}}$) Flow

Modeling results*, including:

- neoclassical poloidal ion velocity (no toroidal flow)
- shearing by turbulence-driven and $\nabla p$ driven $E \times B$ flow
- pressure profile evolution (radial transport)

*based on Miki, Diamond, PoP 2012

Total $E \times B$ flow (includes $v_{\theta}$, $v_{\text{Dia}}$, and turbulence-driven flow): ($E_r, \nabla h$) phasing shifts from 90° closer to 0° as diamagnetic shear becomes dominant
Predator-Prey Model Predicts LCO with Opposing Turbulence-Driven and $\nabla p$-Driven ($v_{\text{Dia}}$) Flow

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Total $E \times B$ flow (includes $v_{\theta}$, $v_{\text{Dia}}$, and turbulence-driven flow): ($E_r, \bar{n}$) phasing shifts from 90° closer to 0° as diamagnetic shear becomes dominant
Predator-prey Model Qualitatively Reproduces the Measured Phase Shift between $\bar{\eta}$ and $v_{\text{ExB}}$

Early LCO ($t_0 + 1.5\text{ms}$):
- Experiment: $\Delta\phi \approx 70-90^\circ$
- Model: $\Delta\phi \approx 50-70^\circ$

Late LCO ($t_H - 1.5\text{ms}$):
- Experiment: $\Delta\phi \approx 20-30^\circ$
- Model: $\Delta\phi \approx 10-20^\circ$

Quantitative differences due to variations of Zonal- and mean turbulence-driven ion flow
E × B and v × B seed flow shear at the L-mode-LCO Transition
Importance of Seed Flow Shear: L-Mode $E \times B$ and $v \times B$ Flow Shear (and $P_{th}$) Increase at Low and High Density

- Reynolds work $P_{Re}$ depends on Reynolds stress and seed shear flow:
  \[ P_{Re} = \langle \tilde{v}_r \tilde{v}_\theta \rangle \frac{\partial \langle v_\theta \rangle}{\partial r} \]

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

- L-mode diamagnetic seed flow shearing rate $\omega_{Dia}$ does not reflect the $P_{th}$ density dependence
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 $E \times B$ shear and $v \times B$ 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 $\tilde{n}$

- $E \times B$ Shearing rates peak in the outer shear layer where turbulence level is high.
- Positive flow transients suppress turbulence.
Negative Flow Transients Occur after Turbulence Suppression

- Negative $E \times B$ transients reflect turbulent-driven flow early in the LCO.
- Pressure-gradient-driven flow only changes significantly well into the LCO.
Predator-Prey Model Predicts LCO with Opposing Turbulence-Driven and $\nabla p$-driven ($v_{D\text{ia}}$) 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-driven Zonal flow** $v_{ZF}$ lags density fluctuation level $\tilde{n}$ by $90^\circ$

**Equilibrium flow** is out of phase ($180^\circ$) with $\tilde{n}$ (both consistent with observed limit cycle phasing)
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

**Predator-Prey Model Predicts LCO with Opposing Turbulence-Driven and \( v_{ZF} \)-Driven (\( v_{Di} \)) Flow**

Turbulence-driven flow \( v_{ZF} \) lags \( \bar{n} \) by 90° (qualitatively consistent with experiment)

Poloidal Ion Flow lags \( \bar{n} \) by 10-30° consistent with observed limit cycle phasing)
Predator-Prey Model Predicts LCO with Opposing Turbulence-Driven and $v_{ZF}$-Driven (vDia-) 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-driven flow $v_{ZF}$ lags density fluctuation level $\tilde{n}$ by 90° (consistent with observed limit cycle phasing)

* L. Schmitz/EU-US TTF 2014
Flow Layer Propagates Radially Inwards

- Positive transients in inner shear layer delayed;
- Consistent with radial inward propagation of LCO $E \times B$ flow*
- Mesoscale radial structure:
  $\gamma_{i} < L_{E \times B} < L_{p}$

*L. Schmitz et al., PRL 2012
Limit Cycle Directions (\(\tilde{n}, v_{ExB}\) Phase Relation) are Consistent with Meso-scale Turbulence-Driven Flow

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

\(\tilde{n}, v_{ExB}\) phase relationship is consistent with observed radial \(E \times B\) flow propagation

*L. Schmitz et al.,*
Predator-Prey Model Predicts LCO with Opposing Turbulence-Driven and $\nabla p$-Driven ($v_{Dia}$) Flow
Evidence of Turbulence-Driven Poloidal Ion Flow from Main Ion CER and DBS

Poloidal flow acceleration via turbulence-generated Reynolds stress \( \langle \vec{v}_\theta \vec{v}_r \rangle \):

\[
\frac{\partial \langle \vec{v}_\theta \rangle}{\partial t} = - \frac{\partial}{\partial r} \langle \vec{v}_\theta \vec{v}_r \rangle - \mu \langle \vec{v}_\theta \rangle
\]

Main ion flow \( \vec{v} \) lags the density fluctuation level \( \vec{\eta} \)

\( E \times B \) velocity approximately in phase with \( \vec{v} \):

Driven Poloidal ion flow is main contribution to \( \vec{v}_{E \times B} \)

He Plasma: Cross-Correlation of \( \vec{\eta} \) and \( \vec{v} \)

\( \Delta t_D \approx 50 \mu s \)

Measured early in the LCO
Poloidal main ion flow $v_\theta$ (blue, green) lags the density fluctuation level $\bar{n}$

The $E \times B$ flow is in phase with $v_\theta$ (expected if the $E_r$ modulation results from $v_\theta$)

Less clear correlation of $\bar{n}$ with toroidal velocity $v_\phi$ in the early LCO

He Plasma: Cross-Correlation of $\bar{n}$ and $v_{E \times B}$ with $v_\theta$

$C(v_{E \times B}, v_\theta)$
$t_0 + 1.5\text{ ms}$

$C(\bar{n}, v_\theta)$
$t_0$ (2569 ms)

$C(\bar{n}, v_\theta)$
to $+1.5\text{ ms}$

$R=R_s-0.8 \text{ cm}$
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 $v_{\phi}$

Weak toroidal velocity modulation observed in Inner Shear Layer
Miki-Diamond Model* (1-D, coupled with radial transport model)

\[
\frac{\partial}{\partial t} \tilde{I} = \gamma \tilde{I} - c_1 \tilde{I}^2 - \alpha_0 E_0 - \alpha_v E_v
\]

\[
\frac{\partial}{\partial t} E_0 = \frac{\alpha_0 E_0 \tilde{I}}{1 + \zeta_0 E_v} - \gamma_{damp} E_0
\]

\[
\frac{\partial}{\partial t} P_i' = Q - c_2 \tilde{I} P_i' - c_3 \tilde{I}
\]

Turbulence Evolution

Turbulence-driven shear flow energy

Pressure gradient evolution

Mean Shear Flow

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 \( P_{\text{th}} \) on density:

\[
P_{\text{th}}(\text{MW}) = 0.049 B_\Phi^{0.8} n_e^{0.72} S^{0.94} \quad (2008 \text{ multi-machine scaling})
\]

- 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 \( P_{\text{th}} \) scaling
Meso-Scale Dipole Structure of Turbulence-Driven Flow: Alternating Transients in Outer / Inner Shear Layer

$E \times B$ 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 $E \times B$ flow*

*L. Schmitz et al., PRL 2012