The Role of Nonlinear Interactions in Causing Transitions into ETB Regimes

I. Cziegler\textsuperscript{1},
A.E. Hubbard\textsuperscript{2}, J.W. Hughes\textsuperscript{2}, J.H. Irby\textsuperscript{2}, J.L. Terry\textsuperscript{2}, G.R. Tynan\textsuperscript{1}

\textsuperscript{1}University of California, San Diego
\textsuperscript{2}Massachusetts Institute of Technology, PSFC

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Motivation: understanding confinement states and transitions

- **H-mode**: edge transport barrier of heat and mass
- **Significance**: – tokamak plasma phases exist
  – future devices need high pressure
- **Need to predict the L-H transition power threshold**

![Graph showing normalized poloidal flux vs. normalized poloidal flux with H-mode and L-mode represented.](image)

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\[ T_e [\text{eV}] \]
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  ($M_i$, $v_{\phi}$, divertor geometry, etc)

\[ P(MW) = 0.049 B_{\phi}^{0.8} n_e^{0.72} S^{0.94} \]

(Martin, JoP, 2008)
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  Particularly:
  – $B \times \nabla B$ asymmetry
  – intermediary states (I-mode, LCO)
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- Present empirical scaling ignores some real physics  
  \( M_i, v_{\phi_i}, \) divertor geometry, etc
- Particularly:  
  – B×∇B asymmetry  
  – intermediary states (I-mode, LCO)
- Physics-based model:  
  – identify L-to-H transition trigger mechanism  
  – connect turbulence physics to macroscopic scaling

\[ n_e [10^{20} \text{ m}^{-3}] \]
\[ T_e [\text{eV}] \]
\[ \text{normalized poloidal flux} \]
Outline

• Background:
  – turbulence-flow interactions in the L-H transition
  – $B \times \nabla B$ asymmetry: the I-mode and Limit-Cycle-Oscillations

• Turbulence physics in L-mode leading up to confinement transitions

• Flow dynamics in the I-mode regime and accessibility

• Conclusions
Focus on immediate trigger of L-H transition

Study flow dynamics at ~5-10ms around L-H transition...

...in the region where the edge transport barrier forms.
Transient at L-H and the drift-wave/zonal-flow system

- Poloidal flows in the edge are important
- Particularly $E_r$ before evolution of the pressure gradient
- Gradient + electric field lead to feedback loop

Transient at L-H and the drift-wave/zonal-flow system

• Poloidal flows in the edge are important
• Particularly $E_r$ before evolution of the pressure gradient
• Gradient + electric field lead to feedback loop
• Candidate for trigger: predator-prey model
  (Kim, Diamond PRL 2003)
  (Miki, Diamond PoP 2012)
Nonlinear transfer explains initial turbulence reduction and generation of poloidal flow

Turbulent kinetic energy:
\[ \partial_t \tilde{K} = \gamma_{\text{eff}} \tilde{K} - P - \partial_r \tilde{T} \]
\[ \tilde{K} = \frac{1}{2} \langle \tilde{v}_\theta^2 \rangle \]

Large-scale flow energy:
\[ \partial_t \tilde{K} = P - \partial_r \tilde{T} - \nu_{\text{LF}} \tilde{K} \]
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1st order condition on turbulence quenching:
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- nonlinearity leads
- mean shear flow locks in H-mode

Cziegler et al, PPCF 2014/NF 2015
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Transfer is localized to narrow region at edge with shear

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Drift **towards** active X-point
- H-mode threshold $\sim P_{th}(\text{Martin})$
- Below threshold: **LCO** regime, aka “dithers”, aka “I-phase”

Drift **away from** active X-point
- H-mode threshold $\sim 2 \times P_{th}(\text{Martin})$
- Below threshold: **I-mode** (at low $n_e$)
**B×∇B asymmetry: the I-mode and Limit-Cycle-Oscillations**

"Favorable" configuration – for H-mode

- Drift **towards** active X-point
- H-mode threshold \( \sim P_{th} \) (Martin)
- Below threshold: **LCO** regime, aka "dithers", aka "I-phase"

"Unfavorable" configuration

- Drift **away from** active X-point
- H-mode threshold \( \sim 2 \times P_{th} \) (Martin)
- Below threshold: **I-mode** (at low \( n_e \))

Both have further, as yet unexplained sensitivities – \((B_\varphi, n_e, I_p)\)
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Diagnostic setup

Primary diagnostic: **Gas Puff Imaging**

- inject $D_2$ or He, sensitive to $n_e, T_e$
- small toroidal extent ($\sim 5\text{cm}$) allows localization
- 90 channels cover $\sim 4\text{cm} \times 3.6\text{cm}$
- views coupled to avalanche photodiodes (APD), sampled at 2 MHz

- Two-point correlation time delay estimate (TDE):
  \[ \nu_i = \Delta x_i / \tau_d \]
  with a 10μs sample size per point.

- Averaging in analysis involves
  \[ \langle v \rangle = \langle v \rangle_{\theta_i, t} \]
  \[ v = v_{3\text{kHz}} \quad \tilde{v} = v_{50\text{kHz}} \]
Strong transfer from all frequencies observed near threshold power

Bispectral estimate of three-wave coupling with “source” $f_1$ and “target” $f$ freq. resolved

$$T_v(f, f_1) = -\text{Re}(\langle \tilde{v}_\theta(f) \tilde{v}_r(f - f_1) \partial_r \tilde{v}_\theta(f_1) \rangle)$$

**Ohmic L-mode**

no strong transfer of poloidal flow power

**$P_{aux} = 750\text{kW}$**

clear transfer btwn flctns in 5-40 kHz range with aux. power below threshold (favorable geometry)
Quantification of kinetic energy transfer from turbulence to ZF

- Transfer rates defined as sum of transfer function normalized to flow power
- Quantified below some frequency for ZF
- With strong ICRF heating, clear peak is shown
- Other frequencies average to negative value
H-mode-favorable $B \times \nabla B$: more transfer at same heat flux and $n_e$

Sensible control parameter is:

$$P_{\text{net}} = P_{\text{RF,abs}} + P_{\text{oh}} - dW/dt - P_{\text{rad}}$$

- Transfer into zonal flow increases monotonically with $P_{\text{net}}$
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- Transfer is $\sim 2x$ in favorable geom.
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Energy transfer rate into ZF

Sensible control parameter is:

$$P_{\text{net}} = P_{\text{RF,abs}} + P_{\text{oh}} - dW/dt - P_{\text{rad}}$$

- Transfer into zonal flow increases monotonically with $P_{\text{net}}$
- Transfer is $\sim 2x$ in favorable geom.
- Same normalized energy transfer at the H-mode transition in the favorable/unfavorable geometry
- Consistent with threshold asymmetry: strong ZF are needed
Is shear or stress the dominant component in transfer?
Velocity shear still depends strongly on heat flux

Reminder: ZF-production \[ P = \langle \tilde{v}_r, \tilde{v}_\theta \rangle \partial_r \langle v_\theta \rangle \]
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Reminder: ZF-production $P = \langle \bar{\nu}_r \bar{\nu}_\theta \rangle \partial_r \langle \nu_\theta \rangle$

- grad-B asymmetry persists
- velocity shears are clearly distinguishable between favorable/unfavorable
Does shear determine stress? Are other components (e.g. magnetic shear) just as important?

- strong correlation observed
- grad-B asymmetry disappears
- single correlation $\rightarrow$ magnetic shear/stress makes little difference in asymmetry
- Results seem to point to a minimum shear needed for any Reynolds stress to appear
- consistent with eddy shearing mechanism of Reynolds stress generation
Favorable/unfavorable expts go up to different types of transitions

L-H transition  L-I transition

En. transf. rate to ZF ($10^5$ s$^{-1}$)

$P_{\text{net}}$ (MW)

1.2 MA  1.2 MA
1.0 MA  1.0 MA
0.8 MA  0.8 MA

unfav  fav

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I-mode: attractive alternative high confinement regime

- stationary, high energy confinement, low $\tau_p$, ELM-free regime
- explored on C-Mod, AUG and DIII-D, helping to delineate its operational space

Amanda Hubbard, Invited Tues. Afternoon. KI2.00003
Characteristic edge fluctuations: WCM and GAM

- Only regime in Alcator C-Mod with poloidal velocities exhibiting geodesic acoustic modes (GAM)
- GAM: $n=m=0$ electrostatic modes, rotating plasma shells back and forth at moderate frequencies
- Nonlinear studies show GAM responsible for broad frequency range in weakly coherent mode (WCM)
- Which is responsible for unique quality of transport?

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L-I transition on a fine time scale dissimilar to L-H

**L-I transition**

- **D_α**
- **T_e (a)**
- **\( \frac{\tilde{n}_e}{n_0} \)**
- **V_{GAM}**

**L-H transition**

- **D_α**
- **\( \text{grad} \rho_e \ (10^6 \text{keV/m}^4) \)**
- **turbulent energy**
- **V_{E\times B} (km/s)**
- **normalized transfer \( R_t \)**
- **\( \gamma_{\text{eff}} \) **

- No significant D_α drop (mass transport L-mode-like)
- Beginning of heat pulse
- Total turbulence power **not affected**
- Onset of GAM (due to \( T_e \) rise, \( \nu_\parallel \) drop)

\[
-\left( \langle \tilde{v}_r \tilde{v}_\theta \rangle \partial_r \langle v_\theta \rangle \right) \frac{1}{\langle v_\theta^2 \rangle \gamma_{\text{eff}}} R_t \text{-like term}
\]
Transfer function in unfavorable dir. indicates GAM/ZF competition

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Can transfer function be “continued” into I-mode?

- GAM transfer small but comparable to ZF rates
- I-H transition is still poorly understood
- GAM-ZF competition?
- ZF transfer continues on in the I-mode regime?
- trend of ZF shows plausible I-H mechanism

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Evidence points to role of GAM damping in I-mode access

Neoclassical estimate: \( \gamma = \frac{4}{7}(\nu_{ii}/q) \)

Compared to nonlinear drive

- Damping is compared to nonlinear drive (analogous to ZF-production)
- Demonstrates dependence on T:
  \( \nu_{ii} \propto T_e^{-3/2} \)
- I-mode threshold shown [Hubbard NF12] to scale as
  \( P_{th} \propto I_p \propto 1/q \)
Evidence points to role of GAM damping in I-mode access

Neoclassical estimate: $\gamma = \frac{4}{7}(\nu_{ii}/q)$

- Threshold is also shown to be sensitive to impurities; which is expected due to:

$$\nu_{ii} = f_i \nu_{i-D}$$

where $f_i$ is ion impurity collision factor

- Effective atomic number $Z_{\text{eff}}$ is used as a proxy

- Consistent with difficulty accessing the regime in He plasma
Both GAM and edge coherent mode are crucial for I-mode

**I-mode S(k,f)**

- WCM

**pre-I L-mode**

- edge coherent mode

**Evolution from L-mode**

- Ohmic pre-I I-mode
- df/f=0.1
- df/f=0.7

**C-Mod:**
- coherent mode close to I-mode (seed of WCM without GAM)
- I-mode when GAM appears
- no GAM in L-mode or H-mode

**AUG: [Manz NF ‘15]**
- GAM are present in L-mode
- no high frequency coherent fluctuation
- I-mode when mode appears

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Conclusions

• Measurements of edge flow nonlinearities support predator-prey dynamics

• Kinetic energy transfer in favorable/unfavorable shows a ~2x asymmetry – consistent with strong Zonal Flows being necessary for L-H transition

• Reynolds stress is determined by flow shear, showing relatively minor contribution from magnetic effects

• Transition dynamics are not analogous in L-H and L-I transition with ZF and GAM phenomena, yet:
  
  • Both GAM and edge coherent mode are necessary for I-mode
  
  • Fine details of GAM damping show correlation with I-mode access
Open Questions

• origin of WCM - expect coherent mode!

• origin of the separation of transport channels:
  - high freq driving mass transport?
  - reduction of low freq component?

• Is the ZF still the trigger in the I-H transition?
  – need correct ZF measurement in I-mode
  – compare GAM and ZF transfers
Supplemental material
GAM is responsible for broad frequency range of WCM via nonlinear coupling.

The weakly coherent mode is predominantly a density fluctuation. Consequently, the relevant nonlinear transfer process is:

\[
T_n(f, f_1) = -\text{Re}(\langle \tilde{n}_f^* \tilde{\nu}_{-f_1} \partial_i \tilde{n}_{f_1} \rangle)
\]

\[
\frac{T_n(f, f_1)}{\langle \tilde{n}_f^2 \rangle^{1/2}} \quad \frac{T_n(f)}{\langle \tilde{n}_f^2 \rangle}
\]
Motivation of time-resolved analysis technique

\( \partial_t v_\theta + v_r \partial_r v_\theta = \mu \partial_r^2 v_\theta \)  
Momentum equation for incompressible fluid

\( v = \langle v \rangle + \tilde{v}, \quad \langle \tilde{v} \rangle = 0 \)  
Reynolds decomposition

\[
\partial_t \tilde{K} = \gamma_{\text{eff}} \tilde{K} - P - \partial_r \tilde{T}
\]
kinetic energy in turbulence

\[
\partial_t \bar{K} = P - \partial_r \bar{T} - \nu_{\text{LF}} \bar{K}
\]
kinetic energy in low freq flow

with \( \gamma_{\text{eff}} \) : net difference of drive and decorrelation

\[
\tilde{K} = \frac{1}{2} \langle \tilde{v}_\theta^2 \rangle \quad \bar{K} = \frac{1}{2} \langle v_\theta \rangle^2
\]

Reynolds stress mediated zonal flow production:

\[ P = \langle \tilde{v}_r \tilde{v}_\theta \rangle \partial_r \langle v_\theta \rangle \]

Transport terms in the form of energy flux:

\[ \tilde{T} = \langle \tilde{v}_r \tilde{v}_\theta^2 \rangle / 2 \quad \bar{T} = \langle \tilde{v}_r \tilde{v}_\theta \rangle \langle v_\theta \rangle \]
Sample traces

Low frequency flows: from 3 separate experiments

Poloidal velocity excursion is reproduced in all H-mode favorable transitions regardless of:
- the kind of L-H transition
- magnetic field
- threshold power
- geometry

Time histories are aligned by $D_\alpha$ light drop at $t = 0$ ms

Turbulent velocities
Nonlinear transfer is the dominant quenching mechanism

For a quantitative test of the adequacy of the mechanism to cause the full extent of turbulence quenching, integrate the model Eq.

\[ I_{tr} \equiv \int_{t_{min}}^{t_{max}} \left( P + \frac{\partial r}{\partial t} \tilde{T} - \gamma_{eff} \tilde{K} \right) dt \]

\[ - \int_{t_{min}}^{t_{max}} \partial_t \tilde{K} dt = \Delta \tilde{K}; \]

- Nonlinear energy transfer exceeds the amount that is expected if this is the dominant turbulence quenching mechanism
- radial structure is considered
- turbulence is not homogenous poloidally while flow is
Convergence of bicoherence

- Good sign of convergence for both (bicoherence and transfer) estimators
- Reasonable convergence by ~280 realizations
- Coupling ($b^2$) shows before drive ($T_u$) is significant or
- before I-mode (typical GAM regime in C-Mod)
First order condition on turbulence collapse: terms taking energy from turbulence into zonal flows must exceed the drive. Written with symbols from the model equations:

\[ R_T \equiv \frac{P + \partial_r \tilde{T}}{\gamma_{\text{eff}} \tilde{K}} > 1, \quad \text{1D including the energy-flux-like term} \]

where transfer terms and the kinetic energy are directly calculated, and \( \gamma_{\text{eff}} \) can be estimated from the model Eq. in a stationary L-mode as

\[ \nu_{\text{LF}}|_L = \left[ \frac{\partial_r \langle \tilde{v}_r \tilde{v}_\theta \rangle}{\langle v_\theta \rangle} \right]_{\text{L-mode}} \]

\[ \gamma_{\text{eff}}|_L = \left[ \frac{P + \partial_r \tilde{T}}{\tilde{K}} \right]_{\text{L-mode}} \]

Full L-H transition requires growth of non-turbulence driven shear, ie pressure gradient, to lock in H-mode once turbulence is reduced.