Collaborations:

• Theory
  – Rima Hajjar, Mischa Malkov (UCSD)
  – Zhibin Guo (UCSD→PKU)

• Experiment
  – Rongjie Hong, G. Tynan, HL-2A Team (UCSD and SWIP)

Discussion: Martin Greenwald
Outline

• Basics of Density Limit → Mostly L-mode
  – General Trends
  – Some Indications of Transport as Fundamental
  – Modelling – The Conventional Wisdom

• Recent Studies → HL-2A (L-mode)
  – Edge Shear Layer Evolution as $\bar{n} \rightarrow \bar{n}_g$
  – Shear Layer $\leftrightarrow$ Electron Adiabaticity Connection
  – Synthesis
  – Confronting the Conventional Wisdom
A Theory of Shear Layer Collapse

• Thesis: For hydrodynamic electrons, drift wave turbulence cannot regulate itself via self-generated shear flows. Turbulence levels rise.

• A Simple Argument

• Collisional drift wave-zonal flow turbulence for \( k_H^2 \nu^2_{Te}/\omega\gamma_e \geq 1 \)

• Scaling Comparison

• What of PV Mixing?

• Scenario for edge cooling
Implications and Directions

Some Thoughts on Density Limit in H-mode

Conclusion
Basics of Density Limits
Density Limits

- Not a review! Incomplete!
- Greenwald density limit:
  \[ \bar{n} = \bar{n}_g \sim \frac{I_p}{\pi a^2} \]
- Global limit
- Simple dependence
- Begs origin of \( I_p \) scaling?!
- Most fueling via edge \( \rightarrow \) edge transport critical to \( \bar{n} \) limits
- Manifested on other devices (more later)
  - See especially RFP
• Trends well established

• Often (but not always!) linked to:
  – MARFE (radiative condensation instability) ↔ Impurity influx
  – MHD disruption
  – Divertor detachment
  – H→L Back-transition
• Argue:
  – ‘Disruptive’ scenarios secondary outcome, largely consequence of edge cooling, due fueling
  – \( \bar{n}_g \) reflects fundamental limit imposed by particle transport

• Some Evidence
  – Density decays non-disruptively after pellet injection
  – \( \bar{n} \sim I_p \) asymptote
  – Density limit enforced non-disruptively!

(Alcator C)
• More Evidence:

- Post pellet density decay rises with $\bar{J}/\bar{n}$
- Limit at: $\bar{J}/\bar{n} \sim 1$
- Pellet in DIII-D beat $\bar{n}_g$
- Peaked profiles $\leftrightarrow$ enhanced core particle confinement $\sim$ ITG turbulence
- Reduced particle transport $\Rightarrow$ impurity accumulation
Looking at the Edge

- **Edge Fueling** ↔ **edge transport** crucial to density limit

- C-Mod SOL profiles
- As $n \uparrow$, high $\perp$ transport region extends inward

- Scan of edge/SOL profiles, $\bar{n} \rightarrow \bar{n}_G$
- Large fluctuation activity develops in main plasma, inward from SOL, for $\bar{n} \rightarrow \bar{n}_G$
Tentative Conclusions

- Turbulence intensities
- Particle transport increases
- Pellet injection admits $\bar{n} > \bar{n}_g$, with non-disruptive relaxation, as edge cooling avoided

Key Question:

→ What physics is under-pinning of rise in turbulence, transport as $\bar{n} \to \bar{n}_g$?
Conventional Wisdom  (Rogers + Drake ‘98)

Reduced Fluid Simulation (no heat source)

- D+R on n-limit physics:
  - DWT $\rightarrow$ resistive ballooning turbulence
  - State of high $\nabla P, \beta$, cool electrons
  - Check: $\gamma > \omega_s, \omega_*$?

\[\alpha_{MHD} = -R q^2 \frac{d\beta}{dr}\]

$\leftrightarrow \nabla P \rightarrow$ ballooning drive

\[\alpha_d = \rho_s C_s t_0 / L_n L_0\]

\[t_0 = \frac{(R L_n^2)^{1/2}}{C_s}\]

\[L_0 = 2\pi q \left(\frac{\gamma e R \rho_s}{2 \Omega_e}\right)^{1/2}\]

$\rightarrow$ Hybrid of drift frequency and adiabaticity
So, Conventional Wisdom ➔

- In density limit conditions, another linear instability - resistive ballooning – emerges and dominates
- Transition mechanism/physics not addressed
- Is there more to this than convention?
Recent Studies on HL-2A

(Ronjie Hong, Tynan, P.D., HL-2A Team/NF2018)

New twist: Edge Fluctuation Studies! (L-mode)

- Edge Langmuir probe array
- Curiously absent from $\bar{n}$ limit literature
Basic Results

- OH, $I_p \sim 150 kA$, $B_T = 1.3T$, $q = 3.5 \rightarrow 4$
- $\bar{n} = 0.25 \rightarrow 0.9 \bar{n}_g$
- Profiles

Fluctuation Properties

$\langle V_\theta \rangle$

(phase)

$\langle \tilde{V}_r \tilde{V}_\theta \rangle$

$P_{Re} = -\langle V_\theta \rangle \partial_r \langle \tilde{V}_r \tilde{V}_\theta \rangle \rightarrow$ energy gained by low-f flow

DROPS as $\bar{n} \rightarrow \bar{n}_g$
Further Studies of Stress and Flows

- Flow shearing rate drops as collisionality increases

- Reynolds power (to flow) drops as collisionality increases

cf: Schmid, et. al. 2017
Further Studies

- Joint pdf of $\tilde{V}_r, \tilde{V}_\theta$ for 3 densities

- $r - r_{sep} = -1an$

- Note:
  - Tilt lost, symmetry restored as $\tilde{n} \rightarrow \tilde{n}_g$
  - Consistent with drop in $P_{Re}$ ➔ Weakened production by Reynolds stress
Transport

\[ \langle \tilde{V}_r \tilde{n} \rangle \]

\[ \langle \tilde{n}^2 \rangle^{1/2} \]

\[ \langle \tilde{V}_r^2 \rangle^{1/2} \]

Corr

- \( \Gamma_n \) rises as \( \bar{n} \rightarrow \bar{n}_g \)
- Density fluctuations rise dramatically.
The Key Parameter

- Electron adiabaticity emerges as the telling local parameter $k ||^2 V_{the}^2 / \omega \gamma$
- Drops from $\sim 3 \rightarrow 0.5$ during $\bar{n}$ scan

- Reynolds work plummets as $k ||^2 V_{the}^2 / \omega \gamma \ll 1$
- $P_{Re} \downarrow$ as shear layer weakens
- Turbulent particle flux rises as $P_{Re} \downarrow$
The Feedback Loop (per experimentalists)

- $k_{\parallel}^2 V_{\text{the}}^2 / \omega \gamma > 1$ to $< 1$
  - Weakens ZF (how?)
  - Enhances turbulence
- Increased turbulent transport cools edge

Unpleasantries
The Key Question

- What is fate of ZF for hydrodynamic electrons $(k_{\parallel}^2 V_{th e}^2 / \omega \gamma < 1)$? Underlying Physics?
- How reconcile with our understanding of drift wave-zonal flow physics?
A Theory of Shear Layer Collapse
(R. Hajjar, P.D., Malkov)

Thesis:  - For hydrodynamic electrons, ZF production by drift wave turbulence drops
          - DWT cannot regulate itself by zonal flow shears
          - Turbulence, transport rise
N.B.

• Many simulation studies note weakening or outright disappearance of ZF in hydro. Regime
  – Numata, et. al. ‘07
  – Gamargo, et. al. ‘95
  – Ghantous & Gurcan, ‘15
  ...
  – However, mechanism left un-addressed, as adiabatic electron regime of primary interest
Model: \{ \text{Collisional Drift Wave} \\
\text{Hasegawa-Wakatani} \}

\[ \frac{dn}{dt} = -\frac{v_{th}^2}{\nu_{ei}} \nabla^2 (\phi - n) + D_0 \nabla^2 n \]

\[ \frac{d\nabla^2 \phi}{dt} = -\frac{v_{th}^2}{\nu_{ei}} \nabla^2 (\phi - n) + \mu_0 \nabla^2 (\nabla^2 \phi) \]

\[ \alpha = \frac{k^2 v_{th}^2}{\omega \gamma} \rightarrow \text{coupling parameter} \]

\[ \rightarrow \text{Adiabaticity parameter} \]

- Fluctuations

\[ \partial_t \tilde{n} + \tilde{v}_x \cdot \nabla \tilde{n} = -\frac{v_{th}^2}{\nu_{ei}} \nabla^2 (\tilde{\phi} - \tilde{n}) - \{ \tilde{\phi}, \tilde{n} \} + D_0 \nabla^2 \tilde{n} \]

\[ \partial_t \nabla^2 \tilde{\phi} + \tilde{v}_x \cdot \nabla \nabla^2 \tilde{\phi} = -\frac{v_{th}^2}{\nu_{ei}} \nabla^2 (\tilde{\phi} - \tilde{n}) - \{ \tilde{\phi}, \nabla^2 \tilde{\phi} \} + \mu_0 \nabla^2 (\nabla^2 \tilde{\phi}) \]

- Mean Fields:

\[ \partial_t \tilde{n} = -\partial_x \langle \tilde{V}_x \tilde{n} \rangle + D_0 \tilde{V}_x^2 \tilde{n} \]

\[ \partial_t \nabla_x^2 \phi = -\partial_x \langle \tilde{V}_x \nabla^2 \tilde{\phi} \rangle + \mu_0 \nabla_x^2 \nabla_x^2 \phi \]
A Simple Argument: Wave Propagation (Quasilinear)

- Fundamental dispersion character charges between $\alpha > 1$ and $\alpha < 1$, i.e.

- $\alpha > 1 \rightarrow$ traditional ‘drift wave’ scaling

$$\omega = \frac{\omega_*}{1 + k_1^2 \rho_\parallel^2} + i \frac{\omega_* e k_1^2 \rho_\parallel^2}{\alpha}, \quad \alpha > 1$$

\[ \text{wave + inverse dissipation} \]

- $\alpha < 1 \rightarrow$ hydrodynamic ‘convective cell’ scaling

- $\omega = \left( \frac{|\omega_*| |\hat{\alpha}|}{2k_1^2 \rho_\parallel^2} \right)^{1/2} \left( 1 + i \right), \quad \hat{\alpha} = \frac{k_\parallel^2 \nu_{th}^2}{\gamma}$

\[ \text{Cell} \]
Ubiquity of Zonal Flow?

- ‘Standard argument’: ZF $\rightarrow$ made of minimal $Dl^2 H$
- My favorite: (GFD)

“… the central result that a rapidly rotating flow, when stirred in a localized region, will converge angular momentum into the region” (Isaac Held, ’01)
Why?

• Direct proportionality of wave group velocity to Reynolds stress $\leftrightarrow$ spectral correlation $\langle k_x k_y \rangle$

i.e.

$$\omega_k = -\beta \frac{k_x}{k^2} : \text{(Rossby)}$$

$$V_{g,y} = 2\beta \frac{k_x k_y}{(k^2)^2}$$

$$\langle \tilde{V}_y \tilde{V}_x \rangle = -\sum_k k_x k_y |\phi_k|^2$$

So: $V_g > 0$ ($\beta > 0$) $\iff$ $k_x k_y > 0 \Rightarrow \langle \tilde{V}_y \tilde{V}_x \rangle < 0$

• Outgoing waves generate a flow convergence! $\Rightarrow$ Shear layer spin-up
But for hydro limit:

- \( \omega_r = \left[ |\omega_e| \alpha \right]^{1/2} \)

- \( V_{gr} = -\frac{2k r \rho_s^2}{k^2 \rho_s^2} \omega_r \quad \leftrightarrow \quad \langle \tilde{V}_r \tilde{V}_\theta \rangle = -\langle k_r k_\theta \rangle \)

\( \rightarrow \) Link between energy, momentum flux link weakened

\( \downarrow \)

\( \rightarrow \) Eddy tilting (\( \langle k_r k_\theta \rangle \)) does not arise as consequence of causality

\( \Rightarrow \) ZF generation not ‘natural’ outcome in hydro regime!
N.B. Issue is somewhat non-trivial in that:

- Symmetry breaking $\leftrightarrow \nabla n$
- Mode coupling
- PV mixing

→ All persist in hydrodynamic regime

→ Need look in depth
Reduced Model

• Utilize models for real space structure to address shear layer
  e.g. { Balmforth, et. al. \rightarrow \text{Outgrowth of}
  Ashourvan, P.D. \text{staircase studies}

See also: J. Li, P.D. ‘2018 (PoP)

• Exploit PV conservation:
  \[ q = \ln n - \nabla^2 \phi \rightarrow \text{conserved PV} \]
  \[ \tilde{q} = \tilde{n} - \nabla^2 \tilde{\phi} \]

So

• Natural description: \( \langle n \rangle, \langle \nabla^2 \phi \rangle, \langle \tilde{q}^2 \rangle = \varepsilon \)
  \( \varepsilon = \text{fluctuation P.E.} \)
Reduced Model, cont’d

\[ \partial_t n = -\partial_x \Gamma_n + D_0 \nabla_x^2 n \]
\[ \partial_t u = -\partial_x \Pi + \mu_0 \nabla_x^2 u \]
\[ \partial_t \varepsilon + \partial_x \Gamma \varepsilon = -(\Gamma_n - \Pi)(\partial_x n - \partial_x u) - \varepsilon^2 + P \]

- Fluxes:
  \( \Gamma_n \rightarrow \text{Partial flux } \langle \tilde{V}_x \tilde{n} \rangle \)
  \( \Pi \rightarrow \text{Vorticity flux } \langle \tilde{V}_x \nabla^2 \tilde{\phi} \rangle = -\partial_x \langle \tilde{V}_x \tilde{V}_y \rangle \) (Taylor)
  \( \Gamma \varepsilon \rightarrow \text{spreading, } \langle \tilde{V}_x \tilde{\varepsilon} \rangle \rightarrow \text{triad interactions} \)

\[ l_{m,k} = \frac{l_0}{\left(1 + \frac{(l_0 \nabla u)^2}{\varepsilon}\right)^{\delta}} \rightarrow l_0 \]
**The Fluxes – Physics Content**

- Proceed by QLT

\[ \Pi = -\chi_y \partial_x u + \Pi_{\text{resid}} \]

- Diagonal, Shear relaxation

- Residual \(\leftrightarrow \nabla n\), via \(\hat{\alpha}\)

- Production \(\rightarrow\) key measure

\[ \Gamma_n = -D_n \nabla n \]

- Primary focus on scalings with \(\alpha\)

- i.e. what changes as \(\alpha > 1 \rightarrow \alpha < 1\)

(K-H ignored)
Basic Results

• Adiabatic ($\hat{\alpha} \gg |\omega|$)

\[
n_0 \Gamma_n = -\frac{\langle \delta v_x^2 \rangle d\bar{n}}{\hat{\alpha} \frac{d\bar{n}}{dx}} \simeq -\frac{\varepsilon l_{mix}^2 d\bar{n}}{\hat{\alpha} \frac{d\bar{n}}{dx}}
\]

\[
\Pi = -\frac{|c_m| \langle \delta v_x^2 \rangle d^2 \bar{v}_y}{|\omega|^2 \frac{d^2 \bar{v}_y}{dx^2}} - \frac{\omega c_i \langle \delta v_x^2 \rangle d\bar{n}}{\hat{\alpha} \frac{d\bar{n}}{dx}} \left( \frac{k_{s}^2 \rho_s^2}{1 + k_{s}^2 \rho_s^2} \right)
\]

\[
\simeq -\frac{\varepsilon l_{mix}^2 d^2 \bar{v}_y}{\hat{\alpha} \frac{d^2 \bar{v}_y}{dx^2}} - \frac{\omega c_i \varepsilon l_{mix}^2 d\bar{n}}{\hat{\alpha} \frac{d\bar{n}}{dx}}
\]

• Reduction:

\[
\Gamma_n \simeq -\left( \frac{\varepsilon l_{mix}^2}{\hat{\alpha}} \right) \nabla \bar{n}
\]

\[
\chi_y \simeq \varepsilon l_{mix}^2 / \hat{\alpha}
\]

\[
\Pi^{res} \simeq -\left( \omega c_i \varepsilon l_{mix}^2 / \hat{\alpha} \right) \nabla \bar{n}
\]
Results, cont’d

- Hydrodynamic ($\hat{\alpha} \ll |\omega|$)

\[
\begin{align*}
n_0\Gamma_n \approx & -\frac{\sqrt{k_1^2 \rho_s^2}}{2k_0 \rho_s c_s} \sqrt{\frac{|dn/dx|}{\hat{\alpha}}} \langle \delta v_x^2 \rangle \approx -\frac{\epsilon l_{mix}^2}{\sqrt{\hat{\alpha}|\omega^*|}} \frac{dn}{dx} \\
\Pi = & -\frac{\gamma_m}{|\omega|^2} \frac{d^2\bar{v}_y}{dx^2} - \frac{\omega_c \langle \delta v_x^2 \rangle}{k_0 \rho_s c_s} \cdot \sqrt{\frac{k_1^2 \rho_s^2}{2}} \sqrt{\frac{\hat{\alpha}}{|\omega^*|}} \\
\approx & -\frac{\epsilon l_{mix}^2}{\sqrt{\hat{\alpha}|\omega^*|}} \frac{d^2\bar{v}_y}{dx^2} - \frac{\omega_c \epsilon \sqrt{\hat{\alpha} l_{mix}^2}}{|\omega^*|^{3/2}} \frac{dn}{dx}
\end{align*}
\]

- Reduction:

\[
\begin{align*}
\Gamma_n \approx & -\left(\frac{\epsilon l_{mix}^2}{\sqrt{\hat{\alpha}|\omega^*|}}\right) \nabla \bar{n} \\
\chi_y \approx & \frac{\epsilon l_{mix}^2}{\sqrt{\hat{\alpha}|\nabla \bar{n}|}} \\
\Pi^{res} \approx & -\left(\omega_c \epsilon \sqrt{\hat{\alpha} l_{mix}^2}/|\omega^*|^{3/2}\right) \nabla \bar{n}
\end{align*}
\]
Shear Strength!

- **Vorticity gradient** emerges as natural measure of production vs. turbulent mixing

  \[ i.e. \quad \Pi_{\text{resil}} \quad \text{vs.} \quad \chi_y \]

- Stationary vorticity flux:

  \[ \nabla u = \frac{\Pi_{\text{resil}}}{\chi_y} \quad \text{n.b.:} \quad u' = (V_y')' \]

  \[ \nabla u \text{ as FOM} \]

- How characterize layer?
Shear Strength, cont’d

- Jump in flow shear over scale D equivalent to vorticity gradient on that scale
- Vorticity gradient characteristic of flow shear layer strength
- N.B. $\nabla u$ central measure of Rossby wave elasticity!

$$l_{Rh} \sim \left(\tilde{V} / \nabla u\right)^{1/2}$$
### Tabulation: $\alpha$ scaling - answer

<table>
<thead>
<tr>
<th>Plasma Response</th>
<th>Adiabatic $\alpha \gg 1$</th>
<th>Hydrodynamic $\alpha \ll 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent enstrophy $\sqrt{\varepsilon}$</td>
<td>$\sqrt{\varepsilon} \propto 1/\alpha$</td>
<td>$\sqrt{\varepsilon} \propto 1/\sqrt{\alpha}$</td>
</tr>
<tr>
<td>Particle Flux $\Gamma$</td>
<td>eq. (20a)</td>
<td>eq. (24a)</td>
</tr>
<tr>
<td></td>
<td>$\Gamma \propto 1/\alpha$</td>
<td>$\Gamma \propto 1/\sqrt{\alpha}$</td>
</tr>
<tr>
<td>Turbulent Viscosity $\chi_y$</td>
<td>eq. (20b)</td>
<td>eq. (24b)</td>
</tr>
<tr>
<td></td>
<td>$\chi_y \propto 1/\alpha$</td>
<td>$\chi_y \propto 1/\sqrt{\alpha}$</td>
</tr>
<tr>
<td>Residual Stress $\Pi^{res}$</td>
<td>eq. (20c)</td>
<td>eq. (24c)</td>
</tr>
<tr>
<td></td>
<td>$\Pi^{res} \propto -1/\alpha$</td>
<td>$\Pi^{res} \propto -\sqrt{\alpha}$</td>
</tr>
<tr>
<td>$\frac{\Pi^{res}}{\chi_y}$</td>
<td>$(\omega_{ci} \nabla \bar{n}) \times$</td>
<td>$\left( \frac{\alpha}{</td>
</tr>
</tbody>
</table>

- **Note:**
  - $\alpha > 1, \nabla u \sim \alpha(0)$
  - $\alpha < 1, \nabla u \sim \alpha$

  i.e. $\chi_y$ rises
  $\Pi_{res}$ drops with $\alpha$

- Fluctuation Intensity rises
- Particle flux rises
Bottom Line

• Shear Layer, via production, collapses as $\alpha \downarrow < 1$

• Transport and fluctuations rise, as $\alpha \downarrow < 1$

• Edge $\alpha = k_{\parallel}^2 V_{th e}^2 / \omega \gamma$ is key local parameter
What of ‘PV Mixing’?

- PV mixing persists in hydro regime
- Key: Unlike GFD/Adiabatic Regime, PV mixed via several channels
- The Cartoons:

\[ \omega + 2\Omega \hat{z} \text{ frozen in} \]
\[ q = \nabla^2 \phi + \beta y \]
PV, cont’d

- H-W:

\[
q = \ln n - \nabla^2 \phi
\]

\[
= \ln(n_0(x)) + \frac{|e| \bar{\phi}}{T} + \bar{h} - \rho_s^2 \nabla^2 \left( \frac{|e| \bar{\phi}}{T} \right)
\]

N.B. Boltzmann response does not contribute to net PV mixing

PV mixing

\[
\Gamma_q = \langle \tilde{V}_x \tilde{h} \rangle - \rho_s^2 \langle \tilde{V}_x \nabla_x^2 \left( \frac{|e| \bar{\phi}}{T} \right) \rangle
\]

Branching ratio?!
PV, cont’d

\[ \Gamma_q = \langle \tilde{V}_x \tilde{h} \rangle - \rho_s^2 \langle \tilde{V}_x \nabla_x^2 \left( \frac{|e|\hat{\phi}}{T} \right) \rangle \]

• \( \alpha > 1 \)
  – Fields \textit{tightly} coupled, \( \sim \alpha \)
  – \( \Gamma_n, \Pi_{rest} \sim 1/\alpha \)
  – \textbf{Both} channels transport PV
  – ZF robust

• \( \alpha < 1 \)
  – Fields \textit{weakly} coupled
  – \( \Gamma_n \sim 1/\sqrt{\alpha}, \Pi_{Rest} \sim \sqrt{\alpha} \)
  – PV transported via \textit{particle flux}
  – ZF dies
Edge Cooling Scenario

- Inward turbulent spreading can increase resistivity and steepen $\nabla j$, resulting in MHD

N.B. For CDW, $Q \sim \Gamma_n$
Implications and Directions
Implications

• Density limit a ‘back-transition’ phenomenon
  
i.e. drift-ZF state $\rightarrow$ convective cell, strong fluctuation turbulence
  
  $\Rightarrow$ scaling of collapse? (spatio-temporal)
  
  $\Rightarrow$ bifurcation? Trigger?, hysteresis?!
  
  $\Rightarrow$ control parameter $\leftrightarrow \alpha$

• Cooling front as secondary
  
  $\Rightarrow$ Extent penetration of turbulence spreading?
  
  $\Rightarrow$ Strength, depth penetration $\Rightarrow$ operating regime
Directions

Experiment

• Test $\alpha$ criticality $\rightarrow \alpha \sim T_e^2/n$. Achieve $\bar{n}/\bar{n}_g > 1$ with $\alpha > 1$?

• $T$ vs $n$ trade-off at $\bar{n}_g$? Sustain $\bar{n} > \bar{n}_g$?!

• Hysteresis in $n$ manifested? Space-time evolution of turbulence

• Localized edge shear layer response to SMBI, small pellets? Relaxation rate, persistence

• Established $\alpha$ vs $\bar{n}/\bar{n}_g$ connection

• Explore changes in bi-spectra $<ZF|DW,DW>$ vs $\bar{n}/\bar{n}_g$ (after Schmid, et. al.)

• Core-edge coupling?
Directions, cont’d

Theory / Model

• As usual, more ‘stuff’ in model...

• N.B. In HL-2A, \( \alpha_{MHD} \uparrow 0.1 \rightarrow 0.3 \)

\[ \alpha \downarrow 3 \rightarrow 0.5 \]

Onset of RBM dubious

• In particular:
  – Neutral penetration – i.e. fueling source
    \( \rightarrow \) CX damping of flows
  – Impurity \( \rightarrow \) build-up
  – \( Q_{e,\text{core}} \) explicit

L\( \rightarrow \)H model of Miki et.al. may be useful
Dynamical Modelling

- Feedback loop
- Macroscopics vs $\alpha$
- Layer scale, expansion
- Heating vs fueling trade-off

- $\bar{n} / \bar{n}_g \leftrightarrow \alpha$ ?
Density Limit in H-mode

- SOL strongly turbulent; pedestal quiescent
- Shear layer at separatrix
- Turbulence penetration of pedestal (H→L BACK Transition) needed for $\bar{n}$ limit phenomena
- SOL turbulence set by:
  - $Q$
  - Fueling
  - Divertor conditions

n.b. SOL curvature unfavorable
Treat via **Box Model** (ZBG, PD 2018)

- $Q_\perp, Q_\parallel$ regulate $I_{SOL}$
- Sufficient $I_{SOL} \rightarrow$ ETB penetration
- What are fueling, $n_{SOL}, Q$ to trigger turbulence in flux and pedestal collapse. Barrier penetration is critical?
- Recent: H-mode density limit set by SOL ballooning?! (SOL $P$ limit) (Goldston, Sun)
Conclusions

• Density limit is consequence of particle transport processes

• L-mode density limit experiments:
  – Edge, turbulence-driven shear layer collapse
  – Local parameter $\alpha = \frac{k_{||}^2 V_{th}^2}{\omega \gamma}$

• Theory indicates:
  – Zonal flow production drops with $\alpha$, $\alpha < 1$
  – Edge transport, turbulence ↑

$\Rightarrow$ Self-regulation fails

• $\bar{n}$-limit in L-mode as transition from drift-zonal turb. $\Rightarrow$ strong drift turbulence