Title
On the Transport Physics of the Density Limit

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Publication Date
2018-11-05

Peer reviewed

On the Transport Physics of the Density Limit

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APS

November, 2018

This research was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, under Award Number DE-FG02-04ER54738.

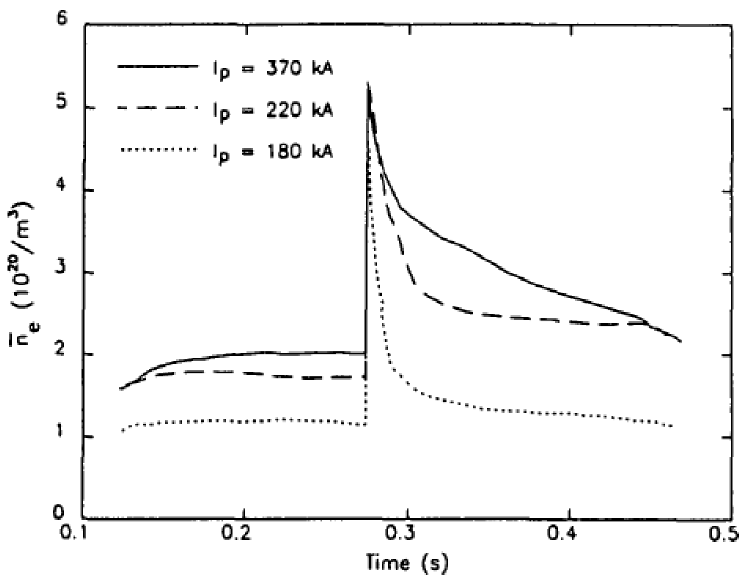
Outline

- Density limit ($\bar{n}/\bar{n}_G \rightarrow 1$) as a transport phenomenon (mostly L-mode)
- Recent experimental studies of the density limit ➔ shear layer collapse
- Theory of shear layer collapse

Thesis: For hydrodynamic electrons, drift wave turbulence cannot self-regulate via flows

- Desperately seeking current dependence
- Implications and Tests

- Density Limit: Edge Transport is Key
  - 'Disruptive' scenarios secondary outcome, largely consequence of edge cooling
  - $\bar{n}_g$ reflects fundamental limit imposed by particle transport (c.f. Greenwald)
- Some Evidence



(Alcator C)

  - Density decays non-disruptively after pellet injection
  - $\bar{n}$ asymptote scales with I_p
  - Density limit enforced by transport-induced relaxation.

Synthesis of the Fluctuation Experiments

- Shear layer collapse and turbulence and D (particle transport) rise as $\frac{\bar{n}}{\bar{n}_G} \to 1$.

- ZF collapse as $\alpha = \frac{k_{||}^2 v_{th}^2}{|\omega| \nu_e}$ drops from $\alpha > 1$ to $\alpha < 1$.

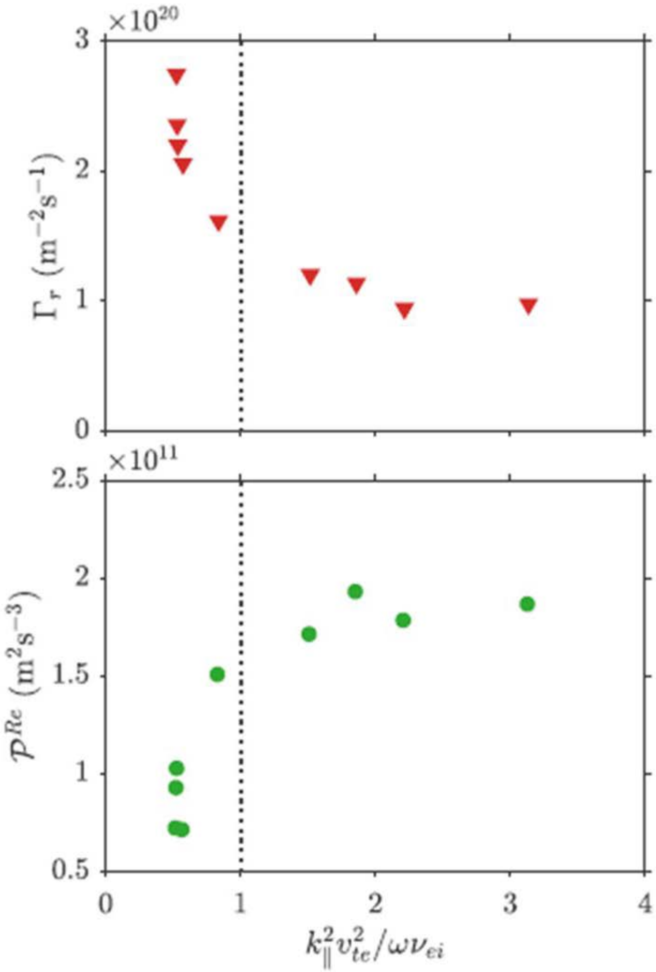
- Degradation in particle confinement at density limit in L-mode is due to breakdown of self-regulation by Z.F.

- Note that β in these experiments is too small for conventional Resistive Ballooning Modes (RBM) explanation.

- How reconcile all these with our understanding of drift wave-zonal flow physics?

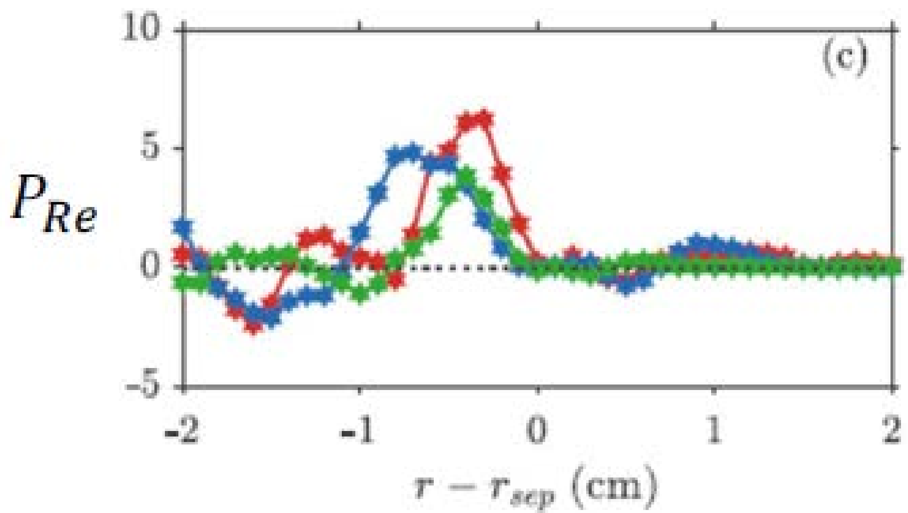
See: Y. Xu, et al. NF 2011
Schmidt, Manz, et al. PRL 2017
Hong, et al. NF 2018

Key Parameter: Electron Adiabaticity



- Electron adiabaticity $\alpha = \frac{k_{||}^2 v_{th}^2}{|\omega|\nu_{ei}}$ emerges as an interesting local parameter. $\alpha \sim 3 \rightarrow 0.5$ during $\bar{n}$ scan!

- Particle flux ↑ and Reynolds power $P_{Re} = -\langle V_\theta \rangle \partial_r \langle \tilde{V}_r \tilde{V}_\theta \rangle$ ↓ as α drops below unity.



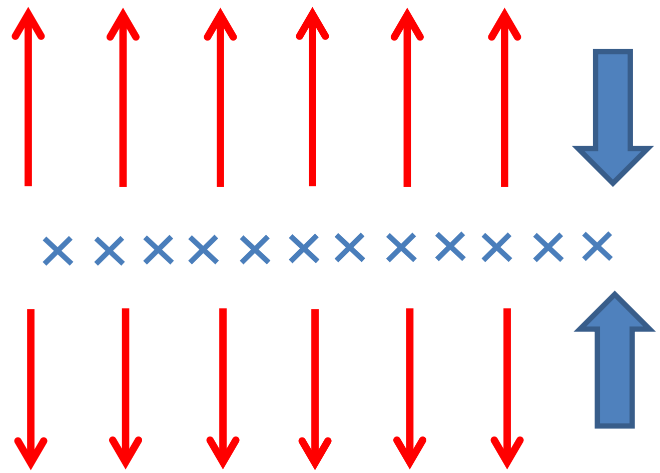
Hong, et al. NF 2018

Why Zonal Flows Ubiquitous?

- Direct proportionality of wave group velocity and wave energy density flux

  to Reynolds stress ←→ spectral correlation $\langle k_x k_y \rangle$

  Causality ←→ Eddy Tilting



i.e.

$\omega_k = -\beta\, k_x / k_\perp^2$: (Rossby)

➔ $V_{g,y} = 2\beta\, k_x k_y / (k_\perp^2)^2$

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

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

- Outgoing waves generate a flow convergence! ➔ Shear layer spin-up

But NOT for hydro limit:

- $\omega_r = \left[\frac{|\omega_{*e}|\hat{\alpha}}{2k_\perp^2\rho_s^2}\right]^{1/2}$
- $V_{gr} = -\frac{2k_r\rho_s^2}{k_\perp^2\rho_s^2}\,\omega_r \quad \overset{?}{\leftrightarrow} \quad \langle\tilde{V}_r\tilde{V}_\theta\rangle = -\langle k_r k_\theta\rangle$

→ Energy, momentum flux no longer directly proportional

↓

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

➔ ZF generation <u>not</u> 'natural' outcome in hydro regime!

Scaling of transport fluxes with α

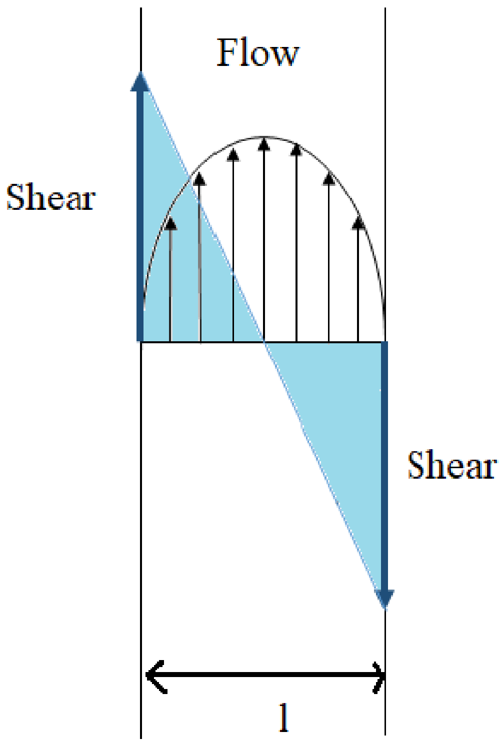
Plasma Response	Adiabatic ($\alpha >> 1$)	Hydrodynamic ($\alpha << 1$)
Particle Flux Γ	$\Gamma_{\text{adia}} \sim \frac{1}{\alpha}$	$\Gamma_{hydro} \sim \frac{1}{\sqrt{\alpha}}$
Turbulent Viscosity χ	$\chi_{adia} \sim \frac{1}{\alpha}$	$\chi_{hydro} \sim \frac{1}{\sqrt{\alpha}}$
Residual stress Π^{res}	$\Pi^{res}_{\text{adia}} \sim -\frac{1}{\alpha}$	$\Pi^{res}_{\text{hydro}} \sim -\sqrt{\alpha}$
$\frac{\Pi^{res}}{\chi} = (\omega_{ci} \nabla n) \times$	$\left(\frac{\alpha}{\lvert\omega_\star\rvert}\right)^0$	$\left(\frac{\alpha}{\lvert\omega_\star\rvert}\right)^1$

$\Gamma_n, \chi_y \uparrow$ and $\Pi^{res} \downarrow$ as the electron response passes from adiabatic ($\alpha > 1$) to hydrodynamic ($\alpha < 1$)

- Mean vorticity gradient ∇u (i.e. ZF strength) becomes proportional to $\alpha \ll 1$ in the hydrodynamic limit.
- Weak ZF formation for $\alpha \ll 1$ → weak regulation of turbulence and enhancement of particle transport and turbulence.

Hajjar, Diamond, Malkov, PoP 2018

Also: Physics of Vorticity Gradient



- Vorticity gradient emerges as natural measure of shear flow strength, sheer stabilization

- $\Pi = 0 \rightarrow \nabla u = \Pi^{res} / \chi_y$

- i.e. production vs. turbulent mixing
- What is physics of vorticity gradient?

A jump in the flow shear over a scale length *l* is equivalent to a vorticity gradient over that scale length

Desperately seeking current dependence

- Obvious? : How does shear layer collapse scenario connect to Greenwald scaling, $\bar{n} \sim I_p$?

- Answer: Neoclassical dielectric ←→ ρ_θ as screening length!

i.e. $\epsilon_{neo} = 1 + 4\pi\rho c^2/B_\theta^2$

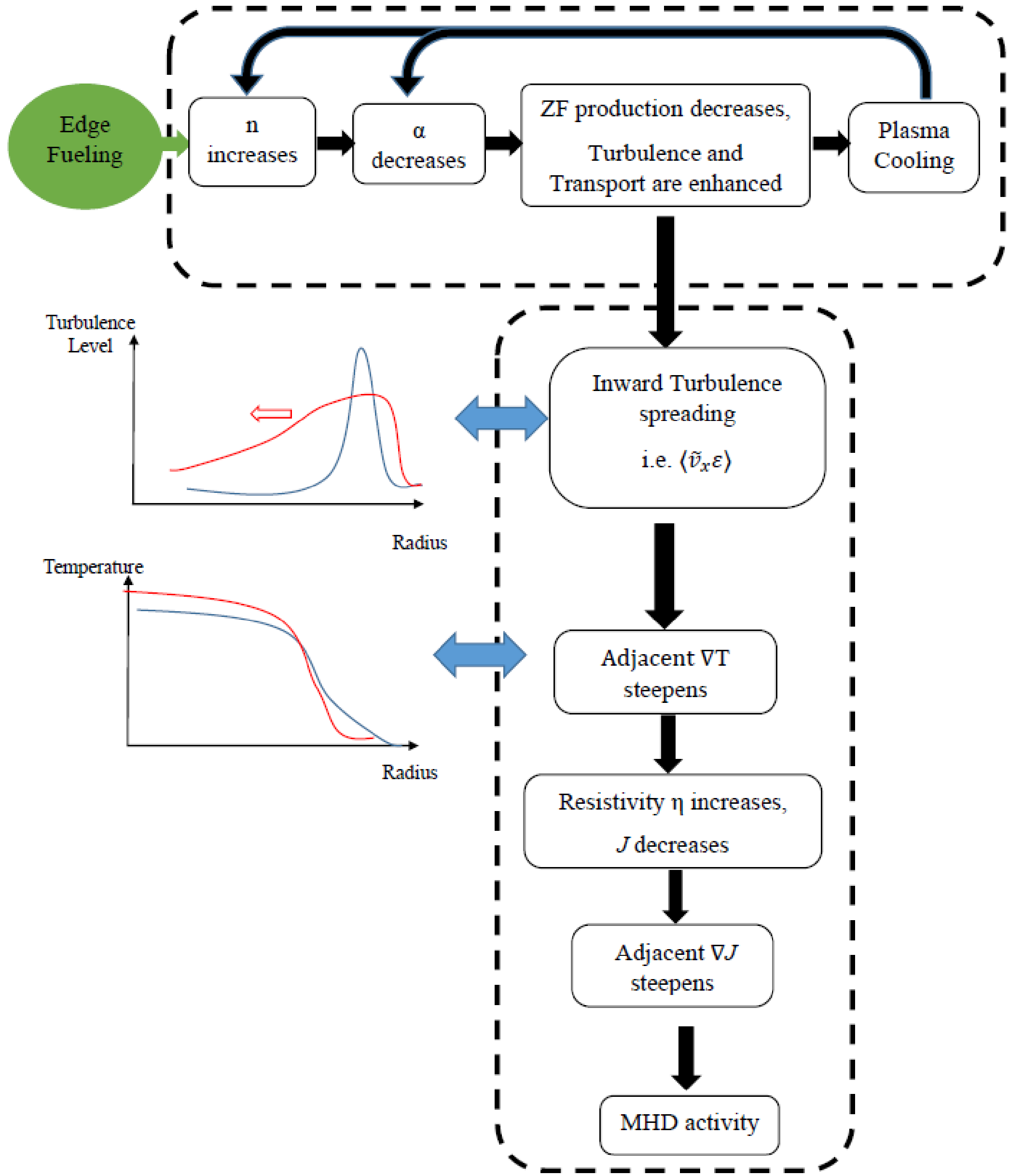
so $\frac{e\hat{\phi}_{zonal}}{T} = \frac{beats(\vec{k},\vec{k}+\vec{q})}{\left(1+1.6\frac{q^2}{\varepsilon^{1/2}}\right)K_r^2\rho_i^2}$

Increasing I_p decreases ρ_θ and offsets weaker Z.F. drive at high I_p (Rosenbluth, Hinton '97)

- N.B.: Applies to RFP as well: neoclassical feeble, but $\rho = \rho_\theta$

➔ Neoclassical response connects shear layer collapse physics to Greenwald scaling.

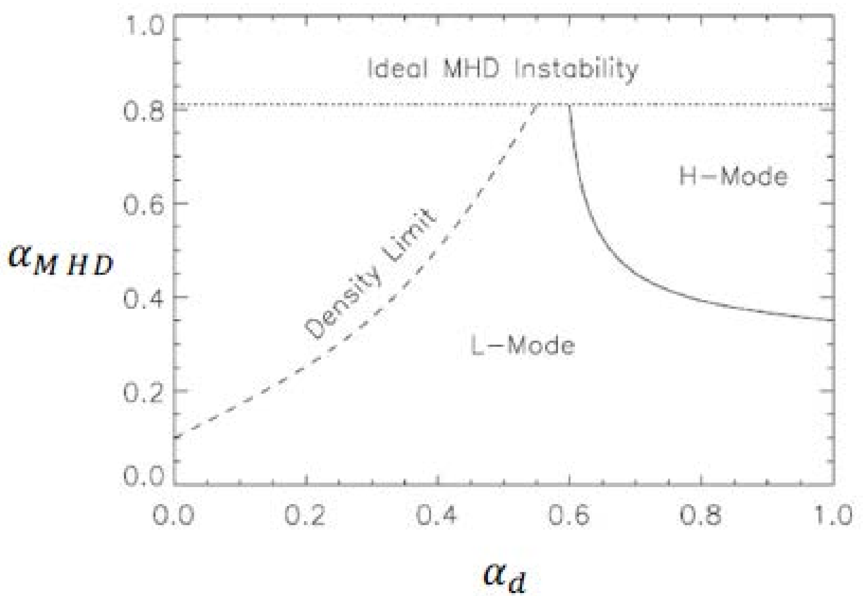
Feedback loop for edge cooling



The Old Story / A Better Story

Modes, Glorious Modes / Self-Regulation and its Breakdown

(Drake and Rogers, PRL, 1998)



- $\alpha_{MHD} = -\frac{Rq^2 d\beta}{dr} \rightarrow \nabla P$ and ballooning drive to explain the phenomenon of density limit.
- Invokes yet another linear instability of RBM.
- What about density limit phenomenon in plasmas with a low β?

(Hajjar et al., PoP, 2018)

State	Electrons	Turbulence Regulation
Base State - *L*-mode	Adiabatic or Collisionless $\alpha > 1$	Secondary modes (ZFs and GAMs)
H-mode	Irrelevant	Mean ExB shear ∇Pi/n
Degraded particle confinement (Density Limit)	Hydrodynamic $\alpha < 1$	None - ZF collapse due weak production for $\alpha < 1$

Secondary modes and states of particle confinement

L-mode: Turbulence is *regulated* by shear flows but not suppressed.
H-mode: *Mean ExB* shear $\leftrightarrow \nabla p_i$ suppresses turbulence and transport.
Approaching Density Limit: High levels of turbulence and particle transport, as shear flows collapse.

Partial Conclusions (L-mode)

- ‘Density limit’ is consequence of particle transport dynamics, edge cooling, etc. secondary.
- Degraded particle confinement – shear layer collapse, breakdown of self-regulation
- Physics: Drop in shear flow production

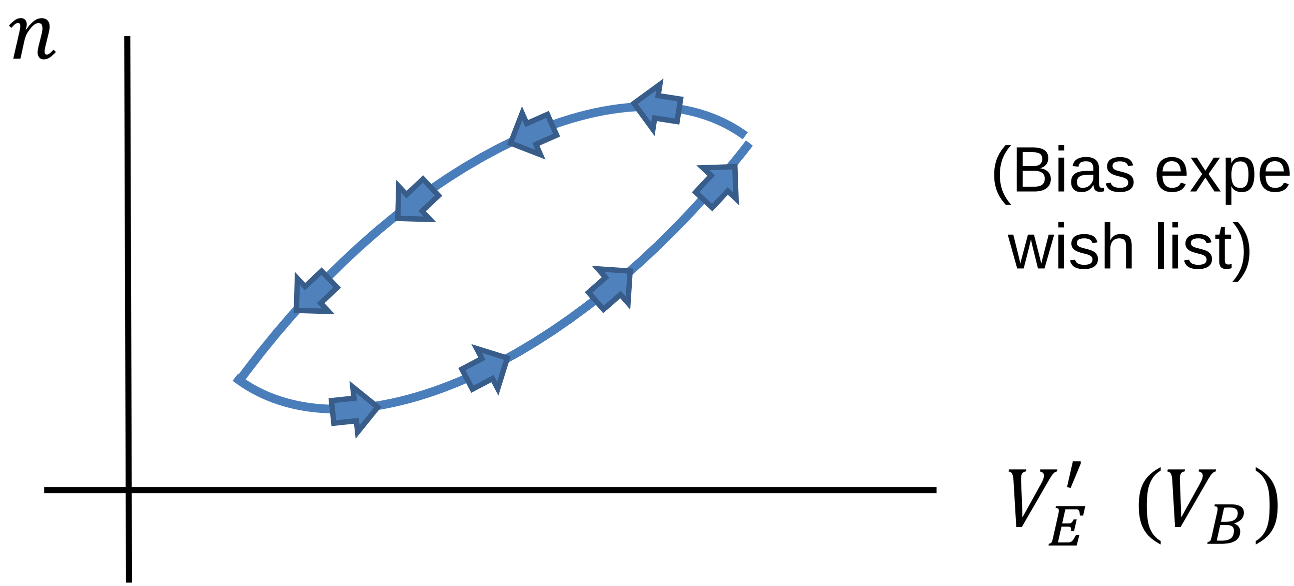
  Key parameter: $k_{\parallel}^2 V_{The}^2 / \omega \nu_e$ (adiabaticity)
- Penetration of turbulence spreading → cooling front, MARFE etc.
- $\bar{n} \sim I_p$ scaling ←→ Zonal Flow screening response !?

Suggestions for Experiment

- Criticality $k_{\parallel}^2 V_{The}^2 / \omega \nu_e$ → T_e^2 / n_e trade off
- Scale of shear layer collapse?
- Turbulence spreading penetration depth?
- Perturbative experiments:
  - SMBI probe of relaxation (with fluctuations)
  - ExB flow drive (Bias) → enhance shear layer persistence?
  - RMP → accelerate shear layer collapse?

N.B. Turbulence/transport part of ‘disruption studies’!

- Explore n, α dependence of flux, stress
- Is shear layer collapse hysteretic?



(Bias experiment, wish list)

- Consider shear layer collapse as transport bifurcation!?

General Conclusions

- Transport is fundamental to density limit. Cooling, etc. drive secondary phenomena.
- Shear layer collapse occurs as transport bifurcation from DW-ZF turbulence to convective cells, approaching density limit.
- Greenwald scaling can result from neoclassical polarization.

Support by U.S. Department of Energy under

Award Number DE-FG02-04ER54738