Dynamics of Edge Shear Layer Collapse and the Denisity Limit

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Abstract

Density limit phenomenology has been associated with the collapse of edge shear layers at high density. Theoretical work has suggested that the onset of such collapse can occur when adiabaticity $\alpha = k_{\parallel}^2 V_{\text{th}}^2/\omega\nu$ drops below $\alpha_{\text{crit}} \approx 1$. Here, we explored shear flow dynamics in a spatially varying density profile in a channel flow configuration. The gradient in adiabaticity triggers the formation of a barrier shear layer, which separates the region of isotropic turbulence from a zonal flow dominated region. The barrier is pinned to the location of α_{crit} and does not propagate. In particular, we observe that this spontaneously generated shear layer forms for $\alpha = \alpha_{\text{cr}}(\kappa)$, and disappears when $\alpha < \alpha_{\text{cr}}$, throughout the domain. This behavior is suggestive of that observed at the density limit, when high edge density forces a drop in the edge layer value of α. Note the results link enhanced particle flux due to the edge shear layer collapse with local edge parameters. The intensity, flux, and $\varepsilon_{\text{turb}}/\varepsilon_{\text{zonal}}$ profiles are calculated. Inhomogeneous mixing of density is observed, suggesting the development of an $\mathrm{E} \times \mathrm{B}$ staircase in the edge layer. Work on the effect of a spatially profiled neutral drag (reflecting a neutral profile) is ongoing. We also plan to explore ?? evolution of density, potential, and neutral density. Emphasis will be on neutral drag effects, but we will also explore neutral entrainment and its impact on transport. More generally, we report on some interesting differences between zonal flow phenomena in the oft-used doubly periodic box, and in channel flows. Specifically:
i) Zonal flows are more coherent in the channel flow case.
ii) A transition curve of $R = \frac{\text{ZF Energy}}{\text{Total Kinetic Energy}}$ is largely monotonic in α for the box. More complex behavior is shown in the case of the channel flow.
iii) Time histories are different for the box and channel cases.

Overview

- Topic: magnetic plasma confinement: edge transport, drift waves, zonal flow generation
- Purpose: Study density limit for the edge zonal flow layer
- Model: Modified Hasegawa-Wakatani System with variable adiabaticity parameter, $\alpha(y) = k_{\|}^2 V_{\mathrm{th}}^2 / \omega_{ci} \eta$
- Channel flow vs. periodic box: benchmarking and comparison
- Scanning ZF amplitude in α for $\alpha = const$ across the flow, zonal flow profiles, ...
- transport barriers and spillovers
- variable α across the channel: ZF localization
- density limit due to shear flow collapse

Modified Hasegawa-Wakatani Model

- two equations: for density and vorticity

$$\frac{\partial \zeta}{\partial t} + \{\phi, \zeta\} = \alpha(y)\left(\tilde{\phi} - \tilde{n}\right) - D\nabla^4 \zeta$$
$$\frac{\partial n}{\partial t} + \{\phi, n\} = \alpha(y)\left(\tilde{\phi} - \tilde{n}\right) - \kappa \frac{\partial \phi}{\partial x} - D\nabla^4 n$$

- $\{f, g\} \equiv (\partial_x f)\,\partial_y g - (\partial_x g)\,\partial_y f$ – Poisson bracket
- $\zeta \equiv \Delta\phi$ – flow vorticity
- DW instability driver $\kappa = n_0^{-1}\partial n_0/\partial y$, $n_0(y)$ – equilibrium density
- n – deviation from equilibrium normalized to n_0
- adiabaticity $\alpha = k_{\parallel}^2 V_{\mathrm{Te}}^2/\eta\omega_{\mathrm{ci}}$, resistivity η

$$\bar{n} \equiv \int n dx, \quad \bar{\phi} \equiv \int \phi dx, \quad \tilde{n} \equiv n - \bar{n}, \quad \tilde{\phi} \equiv \phi - \bar{\phi}$$

Why Channel Flow instead of Doubly-Periodic Box?

Neither is perfect, BUT...

Box

$f\left(x+L_x,y,t\right)=f\left(x,y+L_y,t\right)$
$=f\left(x,y,t\right),$

Pros:

- simple
- some of the channel settings can still be implemented (with limited capacity)
- if rigid boundary is a bad choice, physically

Channel

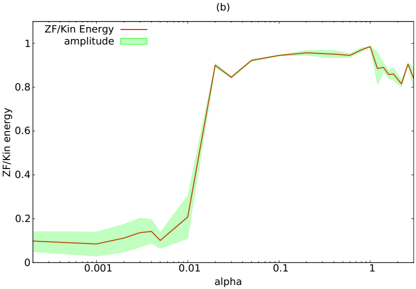
- $f\left(x+L_x,y,t\right)=f\left(x,y,t\right)$
  $f\left(x,0,t\right)\neq f\left(x,L_y,t\right)\ (=C)$

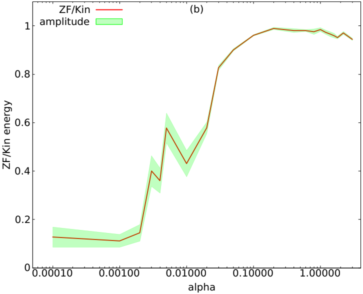
Pros:

- meaningfully apply density, temperature, etc., contrast across the channel
- **impose** $\alpha\left(y\right)$, average shear
- explore geometry (aspect ratio)
- better connect to physical boundary (edge physics)
- wall recycling, fueling, drag,...

Flows with constant α and κ : box - channel ZF generation

$$\epsilon = E_{ZF}/E_k \equiv \int \left(\frac{\partial \phi}{\partial y}\right)^2 dxdy \Bigg/ \int |\nabla \phi|^2 \, dxdy$$



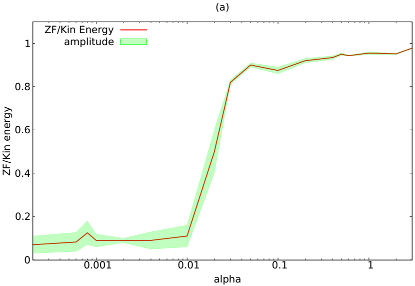


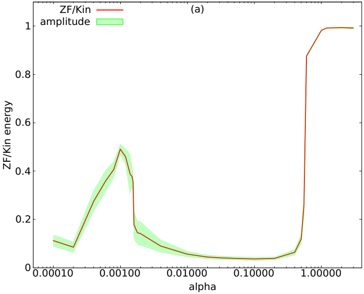
- ϵ vs α scan for flows in a periodic box
  - $\kappa = 0.1$

- ϵ vs α scan for flows in a channel
  - $\kappa = 0.1$

Flows with constant α and κ : box - channel ZF generation

$$\epsilon = E_{ZF}/E_k \equiv \int \left(\frac{\partial\phi}{\partial y}\right)^2 dxdy \bigg/ \int |\nabla\phi|^2 \, dxdy$$

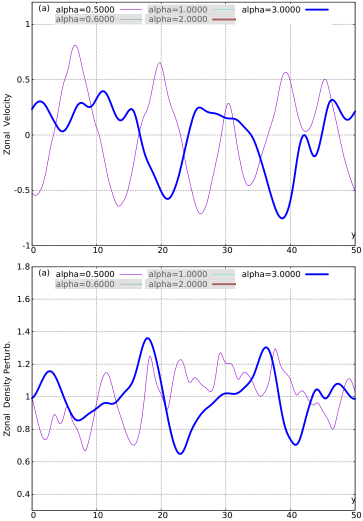




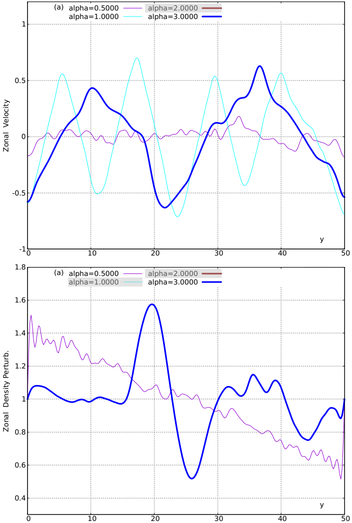
- ϵ vs α scan for flows in a periodic box
  - $\kappa = 0.3$
- ϵ vs α scan for flows in a channel
  - $\kappa = 0.3$

Constant α and κ : box - channel: Zonal Velocity-Density

Periodic Box

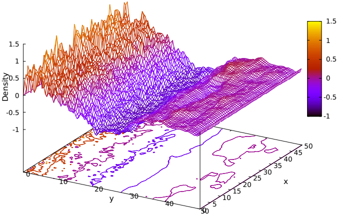


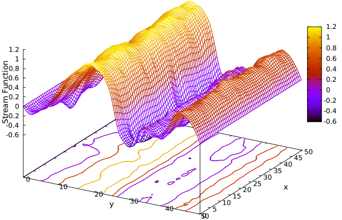
Channel



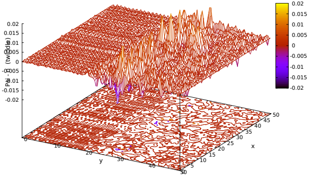
Variable α, channel: Density, Stream function

- $\alpha(y) \propto y$, transport barrier forms where $\alpha \approx \alpha_{cr} \approx 0.3$

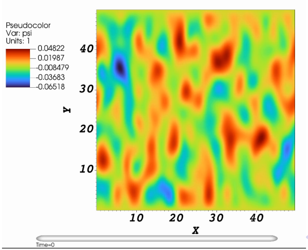




Interaction $\tilde{\psi} - \tilde{n}$



- Stream function movie



Conclusions

- Density limit phenomenology studied using modified HW system with constant and variable adiabaticity parameter $\alpha = k_{\parallel}^2 V_{\text{th}}^2 / \omega\eta$
    - Both periodic box and channel flows simulated and compared
    - Somewhat stronger and coherent channel flows documented
- **Sharp transport barrier forms in the channel where $\alpha(y) \sim \alpha_{\text{cr}}(\kappa)$**
- ZF collapses when density increases as to make α decrease below α_{cr}