Profile Staircases and Edge Shear Layers Near the Density Limit

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Abstract / Objectives

Abstract Edge shear layers, generated by drift waves, collapse when the adiabaticity parameter $\alpha = k_{\parallel}^2 V_{\rm th}^2/\omega\nu$ drops below $\alpha_{\rm crit} \sim 1$. Evolution of $\alpha < \alpha_{\rm crit}$ is thought to be relevant to density limit phenomenology. We have investigated the role of this parameter and the initial density contrast in the formation and dynamics of profiles and shear layers. We use the Hasegawa-Wakatani model, assuming the starting density profile formed after particle injection. Gradient-driven drift waves spontaneously generate a shear flow. The density profile then relaxes under the competition between the turbulent transport and its suppression by the shear flow. The relaxation dynamics generically go through a staircase phase, wherein the initial density step splits into smaller, smoother steps separated by quasi-plateaus. Zonal flows and vortical motion self-regulating the turbulent transport accompany this process. The final extent of the confinement zone depends on the adiabaticity α and the initial density contrast, Δn. Turbulent spreading fronts propagate in both directions from the initial localization of the transport barrier at approximately the same speed, contingent upon the density contrast and adiabaticity parameter. The spreading fronts are consistent with recent experimental findings.[a]

Overview The HW model offers a vital link between the experiments or full-scale 3D simulations and reduced 1- or 0-D physical models. The reduced models often provide a crucial insight into transport bifurcations. We have narrowly tailored the HW model to this end. Apart from the traditional doubly-periodic box setting, we use a channel setting. It accommodates the density/temperature contrasts across the channel, thus elucidating the net-flux-driven turbulence. After benchmarking and comparing our code with the doubly-periodic HW simulations, investigating the zonal flow (ZF) dependence on the model parameters (e.g. number and strengths of ZF jets in the channel vs the adiabaticity $\alpha = k_{\parallel}^2 V_{\rm th}^2/\omega_{ci}\eta$ and instability driver κ) we have focused on two objectives:

(1) Collapse of edge shear layers on a high-density side of the channel, where the adiabaticity α, that acts as a flow bifurcation parameter, drops below $\alpha_{\rm crit} \approx 1$. $\nabla\alpha$ triggers the formation of a barrier shear layer, which separates the region of isotropic turbulence from ZF-dominated. The barrier is pinned to the location of $\alpha_{\rm crit}$ and does not propagate. We observe that this spontaneously generated shear layer forms where $\alpha = \alpha_{\rm crit}(\kappa)$ and disappears where $\alpha < \alpha_{\rm cr}$ inside of the domain (κ is the DW driver). This behavior is consistent with that observed at the density limit when high edge density forces a drop in the edge layer value of α.

(2) Decay and relaxation of a step-like density profile formed after, e.g., a pellet- or supersonic neutral beam injection or other means of build-up. In this simulation set-up, no shear flow is initially imposed but created by the ∇n -driven DWs. Both internal- and edge barriers are formed if $\alpha \sim 1$ and $\Delta n \gg n_{\rm min}$, where $n_{\rm min}$ is the density at the lower-density side of the channel. We observe a noticeable difference between the flux suppression mechanisms on the high- and low-density sides of the transport barrier.

[a] T. Long et al 2021 Nucl. Fusion 61 126066

Modified Hasegawa-Wakatani Model: $\frac{\partial \zeta}{\partial t} + \{\phi, \zeta\} = \alpha\left(\tilde{\phi} - \tilde{n}\right) - D\nabla^4\zeta;\quad \frac{\partial n}{\partial t} + \{\phi, n\} = \alpha\left(\tilde{\phi} - \tilde{n}\right) - \kappa\frac{\partial\phi}{\partial x} - D\nabla^4 n;\quad \zeta \equiv \Delta\phi;\quad \alpha = k_{\parallel}^2 V_{\rm Te}^2/\eta\omega_{\rm ci}$

Here $\{f, g\} \equiv (\partial_x f)\,\partial_y g - (\partial_x g)\,\partial_y f$, $\kappa = n_0^{-1}\partial n_0/\partial y$, where $n_0(y)$ is an equilibrium density profile, and n is a deviation from it, normalized to $n_0(0)$.

Units

$$x/\rho_s \to x,\quad \omega_{\rm ci}t \to t,\quad e\phi/T_{\rm e} \to \phi,\quad n_1/n_0 \to n$$

where $\rho_s = C_s/\omega_{\rm ci}$, $C_s = T_{\rm e}/M$, $n = n_0(y) + n_1$.

Simulation

In most HW doubly-periodic simulations α and κ are constant. As $\kappa \equiv n_0^{-1}dn_0/dy$, $n_0(y)$ is exponential, thus changing by $\exp(\kappa L)$ between the boundaries, which becomes unrealistically high for typical parameters. In a channel setting, we may vary $\kappa(y)$. For example, we use a linear rather than exponential profile of $n_0(y)$, which is more appropriate for the middle part of the pedestal.

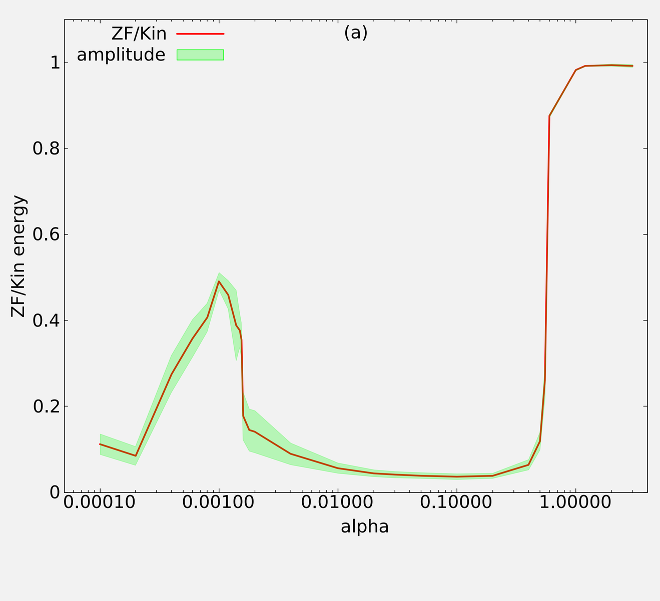
Simulation Results: α -dependence of ZF efficiency — decay of a density step — turbulence spreading — flux suppression by ZF and vortices

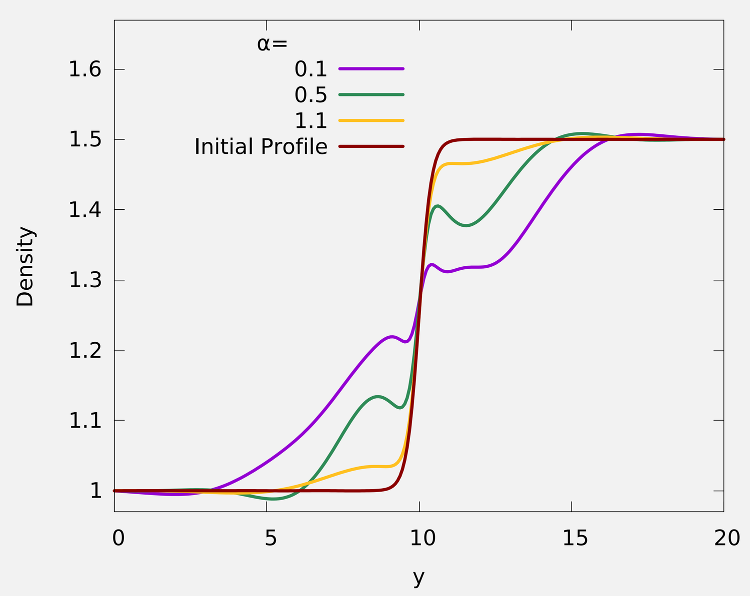
ZFefficiency: $\epsilon = E_{ZF}/E_k \equiv \int(\partial\phi/\partial y)^2\,dxdy \Big/ \int|\nabla\phi|^2\,dxdy$

— ϵ vs α for the channel flows for $\kappa = 0.3$ and relaxation of the initial density step for different α

— **NB**: back transition from a 50% ZF state at $\alpha \ll 1$

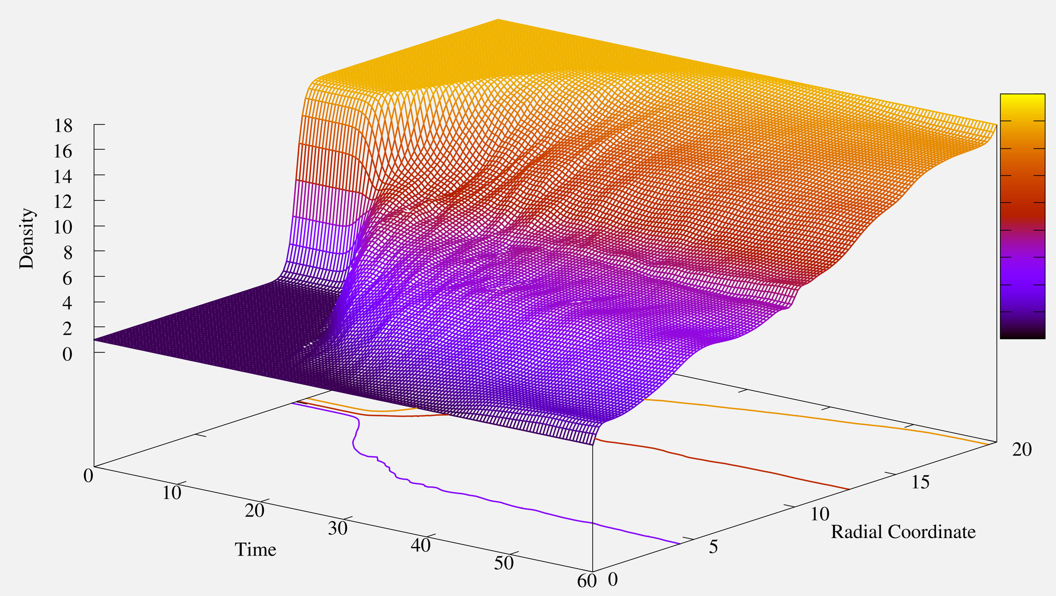
— density gradient inversion due to strong vortices (see a stream function example)

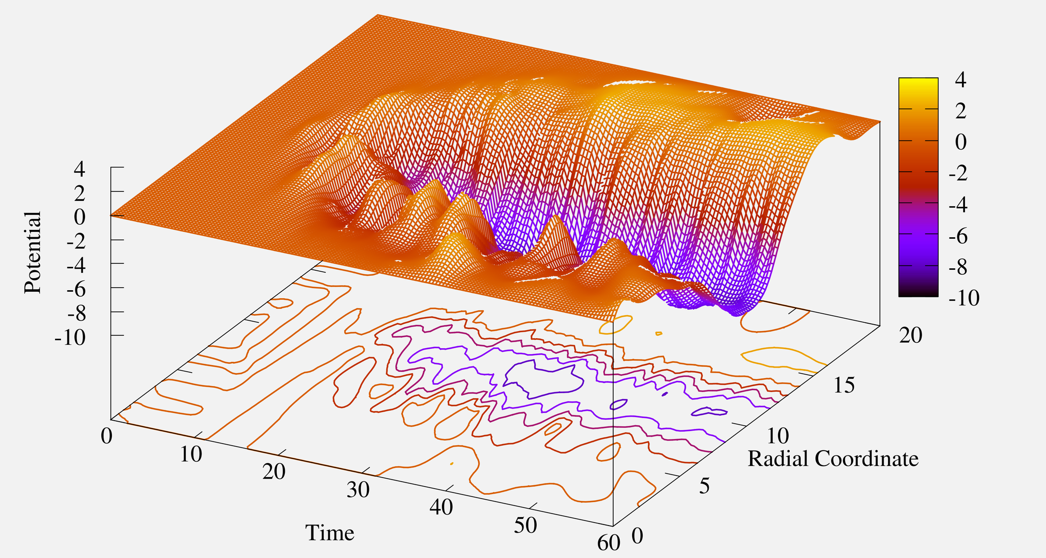




Zonal-averaged density evolution starting from a step profile.

NB: Internal and edge barrier in the final state — staircase-like structure





Stream function, showing strong vortices formed in the foot region of the density landscape and two opposite jets adjacent to the initial density cliff, were the growth rate was at maximum.

Turbulent flux, strogly suppressed after the ZFs and vortices are generated.