Transport and zonal flows dynamics in flux-driven interchange & drift waves turbulence

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Introduction : Cross-field transport, that controls the energy confinement time in tokamaks, is mainly driven by turbulence. In L-mode edge plasmas, the interchange and drift waves instabilities are expected to be dominant. The first one is linked to the magnetic curvature while the second derives from the parallel conductivity [1]. It is observed that the resulting ion-scale turbulence can self-organize into zonal flows (ZFs) that participate efficiently to its saturation [2, 3]. More recently, it has been observed that ZFs can structure into staircases [4], hence producing a set of micro-barriers that can efficiently mitigate avalanche transport.

In this work, the issues of ZFs generation and impact on transport are addressed by means of a reduced flux-driven nonlinear model that features both interchange and drift waves instabilities [5, 6]. The linear properties of both instabilities are controlled by two plasma parameters, the mean curvature g of the magnetic field, and the adiabaticity parameter C that scales like the square of the parallel wave vector divided by the electron-ion collision frequency.

It is shown here that albeit the interchange parameter is controlling the structuration into staircases, the adiabaticity parameter controls the turbulent energy that gets stored in the flows. Moreover, the confinement time normalized to a mixing length estimate exhibits the same dependencies as the energy balance between turbulent modes and zonal flows, attesting the efficiency of nonlinearly generated flows to mitigate turbulent transport.

Tokam1d: a reduced interchange-drift waves model

One considers a magnetized plasma of constant ion T_i and electron T_e temperatures, $\tau = T_i/T_e$, immersed in a constant-in-time magnetic field **B**. The model is solved in a SLAB geometry with *x* and *y* standing for the Cartesian coordinates perpendicular to **B**. The model derives from the electron continuity and charge balance equations. A generalized Ohm's law closes the system,

linking the parallel current to the electric field and the electron pressure gradient.

$$\partial_t N + \{\varphi, N\} = g\partial_y(\varphi - N) + \sigma\nabla_{\parallel}^2(N - \varphi) + D\nabla_{\perp}^2 N + S_N \quad (1)$$

$$\partial_t \Omega + \nabla_{\perp,i}\left\{\varphi, \nabla_{\perp,i}(\varphi + \tau N)\right\} = +(1+\tau)g\partial_y N + \sigma\nabla_{\parallel}^2(N - \varphi) + \nu\nabla_{\perp}^2\Omega \quad (2)$$

The system of equations (1,2) involves the logarithm of the electron density $N = \ln n$ and the generalized vorticity $\Omega = \nabla_{\perp}^2(\varphi + \tau N)$. The nonlinearities are contained in Poisson brackets $\{f, g\} = \partial_x f \partial_y g - \partial_y f \partial_x g$. The magnetic curvature parameter is defined as $g = \frac{2\rho_s}{R}$, with R the major radius of the tokamak and ρ_s the sound Larmor radius. The parallel conductivity is considered constant and is defined as the electron cyclotron frequency to the electron-ion collision frequency $\sigma = \frac{\omega_{ce}}{\nu_{ei}}$. The system is flux-driven with a source of particles S_N and the damping of small scales is ensured by the diffusive terms D and ν.

So as to keep track of nonlinear dynamics while dealing with a more tractable system, the model is further reduced from 3-dimensions to 1 by splitting each field between an equilibrium and a fluctuating component, both depending on (x, t) only. Single parallel and poloidal wave vectors $(k_{\parallel}, k_y)$ are retained for the fluctuating quantities, so that $(\nabla_{\parallel}, \partial_y) \longrightarrow i(k_{\parallel}, k_y)$. The final system of equations then evolves 4 fields. Two real fields for the equilibrium components, N_{eq}, $V_{eq} = \partial_x \varphi_{eq}$, and two complex fields for the fluctuating parts, N_k, Ω_k. The adiabaticity parameter is then defined as $C = \sigma k_{\parallel}^2$.

Turbulent energy gets stored into flows at high C

Simulations are performed using a $N_x = 512$ radial points grid on confinement timescales with $dt = 10^{-1}\omega_{cs}^{-1}$. The adiabaticity parameter C is scanned from 2.10^{-4} to 2.10^{-2} for 2 different values of g: 10^{-4} and 10^{-3}. As a comparison, using WEST tokamak data (major radius $R = 2.5$ m, minor radius $a = 0.5$ m, magnetic field at separatrix $B_{sep} \approx 3$ T), and considering a density of $n_0 = 10^{-19}\ m^{-3}$, temperature of $T_e \approx 100$ eV and safety factor $q_{95} = 5$, one can estimate the instability parameters to be $C = 4.5.10^{-3}$ and $g = 2.6.10^{-4}$.

It is observed that ZFs are generated in every simulations although not at the same intensity. Whenever the flows are artificially switched off, a large scale radial mode tends to grow and the system enters a state of large density gradient building and strong quasi-periodic relaxation events. When flows are retained, it appears that ZFs develop staircase-like structures in interchange dominated simulations (fig 1) meaning at high g for a fixed C.

The total energy is conserved in the simulations. It is possible to define transfer channels from the quadratic terms of the free energy conservation theorem. Among them, most of the energy

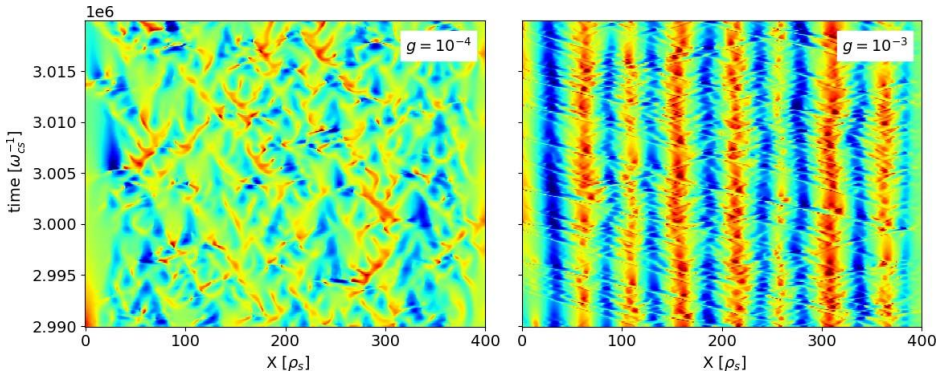

Figure 1: V_{eq} as a function of radius and time for a small (left) and high (right) magnetic curvature g, both performed at $C = 2.10^{-4}$.

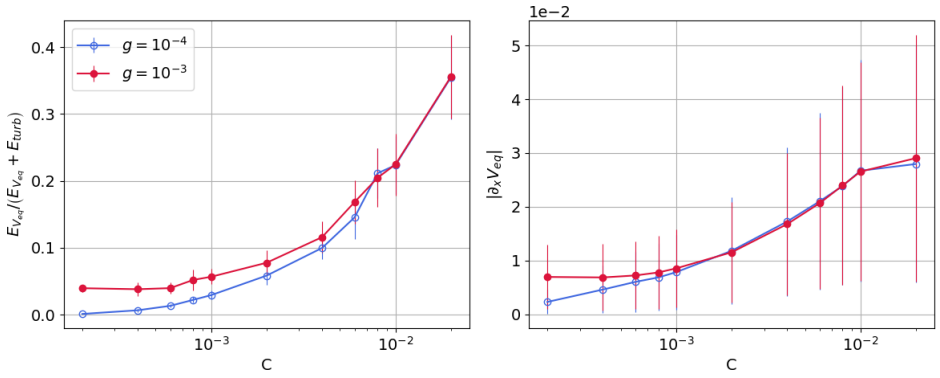

Figure 2: (left) Turbulent energy stored into flows as a function of C for two values of g. (right) Mean shear of velocity.

is stored in the density gradient. The rest is split between the turbulence, E_{turb}, the flows, $E_{V_{eq}}$, and the transfer terms between gradient and flows. It is then possible to study the energy distribution between turbulence and flows depending on the instability parameters, see fig 2. The relative energy stored in the flows tends to increase with the adiabaticity parameter, while the interchange parameter have a little role, if any. Consistently, the mean shear tends to increase as the energy is stored inside the flows.

Confinement time of particles improves with flows

The effect of the flows on the transport is evaluated with the confinement time of the particles for each simulation. The confinement time τ_p is given by the total number of particles (integral of the density profile) divided by the integral of the particle source. This time is mostly governed by the turbulent transport, $\Gamma_{ES} = -2k_y|N_k||\varphi_k|\sin\Delta\phi$, which is largely controlled by the instability parameters as they control the linear growth rate and linear cross-phase $\Delta\phi$. In fig 3, the confinement time of the particles τ_p is compared to a mixing length estimate, $\tau_{ML} = \frac{L_x^2 k_\perp^2}{\gamma_{lin}}$.

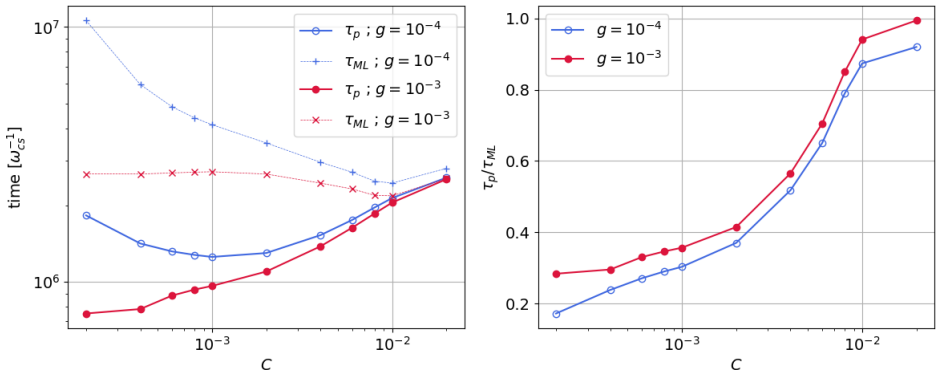

Figure 3: (left) Confinement time of the particles τ_p and mixing length estimate computed from the linear dispersion relation τ_{ML}. (right) Normalized confinement time τ_p/τ_{ML}.

This estimate represents the expected confinement time if the system was following the linear estimations and no flows were created. The linear growth rate γ_{lin} is computed from the dispersion relation of the system where the density gradient is taken from the final equilibrium density profile. Normalizing the particle confinement time with the mixing length estimate highlights the role of the flows to regulate the turbulent transport and increase the confinement. It exhibits the same shape as the energy stored inside the flows and the mean shear.

Conclusion: This paper analyzes the generation and structuration of zonal flows in a competing drift-waves - interchange turbulence using the flux-driven nonlinear Tokam1d code. The energy channels are computed and compared to the global confinement time of the particles. A mixing length estimate is used to normalize the confinement time and focus on the role of flows. The staircases structures are found to emerge mostly in interchange dominated turbulence , i.e. at large g for a fixed C. The energy and shear increase with the adiabaticity parameter with no clear effect of the magnetic curvature. Finally, the normalized confinement time is shown to be consistent with the energy stored in flows.

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