Effects of toroidal and poloidal shear flow in global gyrokinetic simulations

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Abstract

The global gyrokinetic code ORB5 has been modified to allow the treatment of toroidal and poloidal flows with arbitrary profiles and moderate amplitude. We present appropriate canonical background distributions f_0 which are constant along the modified drift orbits in the presence of a background electric field, and allow convenient specification of density, temperature and flow profiles. This approach allows the finite ρ^* terms to be retained in the derivatives of the background distribution in the presence of flows. A nonlinear benchmark is performed at small ρ^* as a comparison against previous results for stabilization of ITG turbulence by toroidal and poloidal shear flows. We recover the strong suppression of turbulence by shear flows, and the additional destabilising effect of parallel velocity shear for large amplitude toroidal flows. For lower q and R/a the effects of parallel velocity shear are weaker, and we show that the turbulence can be entirely quenched even by pure toroidal flows before destabilising effects become dominant. This sets the basis for an exploration of the global dynamics of plasmas with shear flows. As an example we show a linear analysis of a plasma with a V-shaped flow, which models the interface between two zonal flows with opposite sign.

Global gyrokinetic equilibria with background shear flow

The ORB5 code[1] is typically run using a canonical background distribution[2], so that f_0 is constant along the unperturbed gyrocentre orbits. It many other treatments, the background equilibrium is chosen to be a local Maxwellian, and one must either tolerate large transient fluxes at the beginning of the simulation, or ignore terms arising from the derivatives of f_0 along the gyrocentre trajectory. To model plasmas with a background electric potential ϕ_0, we consistently modify the canonical background distribution f_0, and substitute $\phi \to \phi_0 + \phi$ in the zeroth order gyrokinetic equations of motion. We also introduce parallel flows in f_0 such that the sum of the $E \times B$ and parallel flows is either dominantly poloidal, or dominantly toroidal. The

Vlasov-Poisson equations are unmodified, but the equations for δf (which is what is needed in the numerical scheme) are modified. In principle we could add an initial flow as the perturbation δf, but incorporating the flow perturbation in f_0 means that $\delta f/f$ and therefore noise can be reduced, and linear dynamics can be conveniently treated. Note that we do not take into account terms arising from transonic flows $v/v_{th} \sim O(1)$: we will discuss the resulting limitations to our analysis later.

In order for f_0 to be a collisionless equilibrium, it must only be a function of the three canonical momenta: the energy $\varepsilon = mv^2/2 + q\phi_0$, toroidal canonical momentum ψ_c and magnetic moment μ. We suppress the gyroaveraging for the background field ϕ_0, which will vary on scales considerably longer than the gyroradius. We define a canonical Maxwellian

$$f_0 = \frac{n_0(\psi_c)}{(2\pi T(\psi_c)/m)^{3/2}} \exp\left(-\frac{\varepsilon - q\phi_0(\psi_*)}{T(\psi_c)}\right), \tag{1}$$

where $\psi_*(\psi_c, \varepsilon, \mu)$ is a modified canonical toroidal momentum which will be chosen later. To make the dependence on ϕ_0 more explicit, the exponent in the definition of f_0 can be written $[mv^2/2 + q\phi_0(\psi) - q\phi_0(\psi_*)]/T$. The addition of the $q\phi_0(\psi_*)$ term is necessary in order that $\int dv^3 f_0 \sim n_0$, so that the density profile and the electric potential can be independently modified. The equations of motion are as before, except with an $E \times B$ flow incorporated into the equations of motion. Modified terms in the Vlasov equation, $d\delta f/dt = -df_0/dt$, occur due to the new definition of f_0 and the modified zeroth order trajectories.

Choosing $\psi_* = \psi_c = \psi(\vec{R}) + Fv_{\|}B$, the canonical toroidal momentum, results in the a near 'pure toroidal flow' case, with small poloidal flows arising from temperature and density gradients. The poloidal component of the parallel flow along the field line cancels the poloidal flow due to the $E_0 \times B$ motion. Parallel flow appears because $\psi - \psi_c$ is proportional to the parallel velocity, and $\phi_0(\psi_c) - \phi_0(\psi) \propto E_r v_{\|}$: the distribution (ignoring for a moment the density and temperature gradients) is simply a shifted Maxwellian in the small E_r limit. The gyrodensity stays roughly constant, with $\int dv f_0 \sim n_0$, because the perturbation is odd in $v_{\|}$ in this limit.

On the other hand, choosing

$$\psi_* = \psi_{c'} = \psi(\vec{R}) + Fv_{\|}/B - F < v_{\|}/B >, \tag{2}$$

which we call the improved canonical toroidal momentum, results in a state with small parallel flows. Here, the angle brackets denote a bounce average along zeroth order trajectories. $\psi_{c'}$ is equal to the bounce average of ψ, so that is can be considered a good 'average radial position' variable. This choice minimises the distortion to the distribution function f_0 due to ψ_0, by reducing the magnitude of the term $\psi_0(\phi) - \psi_0(\psi_c')$.

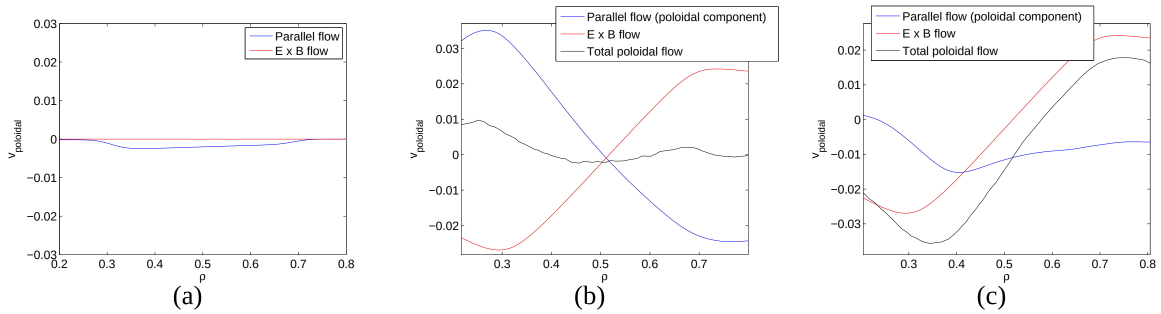


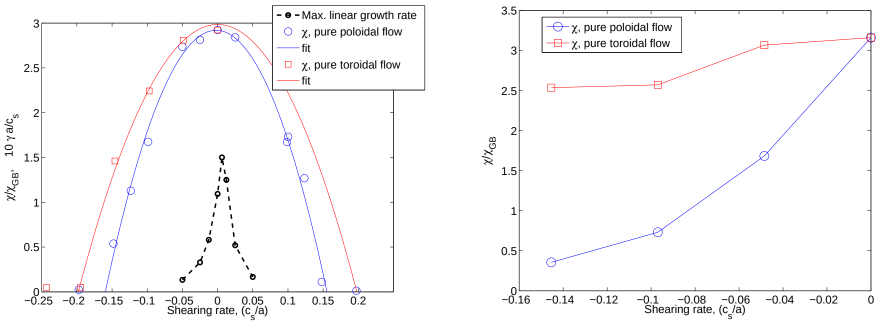
Figure 1: Components of poloidal flow for (a) zero imposed flow (b) imposed 'pure toroidal' flow (c) imposed 'pure poloidal' flow. The poloidal components of flow parallel to B (blue), due to ExB (red), and total poloidal flow (black) are shown.

The local density and mean kinetic energy are not substantially modified by the imposition of a background electric field, for moderate values of the electric field strength. However, in the 'pure poloidal flow' case, once the electrical potential difference across a banana orbit $qE_r\rho_i(a/Rq)^{1/2}$ becomes comparable to the thermal energy, f_0 departs strongly from Maxwellian, and the local gyrodensity is modified. This is also the limit where $v \sim v_{th}$ for the 'pure toroidal flow' equilibria. In either case we are working beyond the limit of our assumptions, so we need $qE_r\rho_i(a/Rq)^{1/2} \ll T_i$.

Linear and nonlinear stability

Two sets of plasma parameters were considered: (1), CYCLONE-like parameters, q=1.4, (r/q) dq/dr=0.8, R/LT=8 at r/a=0.5, a/R=0.36, and (2) 'Waltz standard case' parameters, q=2, (r/q) dq/dr = 1.0, R/LT=9 at r/a=0.5, a/R=0.33. Both were simulated with a circular concentric equilibrium model with adiabatic electrons. For the Waltz parameters, Poloidal shear stabilisation is sufficient to almost completely suppress turbulence. When toroidal shear flow is introduced, the additional destabilising effect of parallel shear flow means there is little overall turbulence suppression. For pure toroidal flows, the poloidal component of the parallel flow cancels the poloidal ExB flow, so $v_{\|} = E_r qR/a$. For the same poloidal shearing rate, the CYCLONE case has weaker parallel flow shear ($dv_{\|}/dr = 3.9 dE_r/dr$), than the Waltz case, with ($dv_{\|}/dr = 6.0 dE_r/dr$ in dimensionless units). The CYCLONE case also has a somewhat lower temperature gradient. The combined effect is that complete stabilisation due to toroidal flow is possible in the CYCLONE case at ω_{ExB}. The suppression of linear growthrates by shear flow is much stronger than the nonlinear suppression, and substantial 'subcritical' turbulence is possible where the system is marginally stable.

As an example of how this formalism can be used to study the dynamics of flow structures, we perform a set of linear simulations of the CYCLONE case with a V-shaped poloidal flow profile,



(a) (b)

Figure 2: Diffusivities for (a) Cyclone case and (b) Waltz standard case versus applied shearing rate.

modelling a plasma with two neighbouring flow zones of opposite sign. Above $R/L_T \sim 6.3$ the plasma is unstable for all values of poloidal flow. This recovers the 'Dimits shift', demonstrating that the reason that self-consisently generated flows cannot always stabilise the turbulence is an instability associated with the interface between two zones.

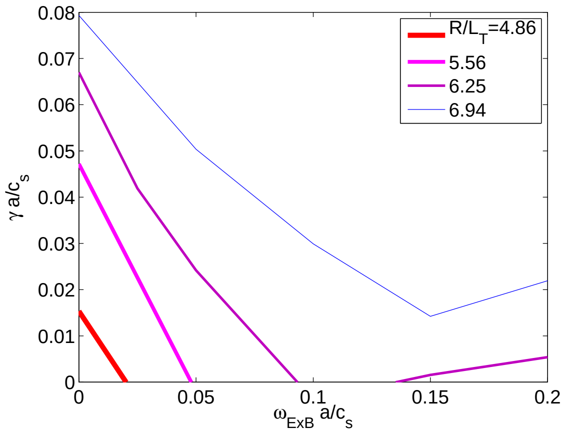


Figure 3: Linear growth rate for simulations with V-shaped flows, versus flow strength, for a range of initial temperature gradients.

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