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Plasma elongation and magnetic shear effects in nonlinear simulations of ITG-zonal flow turbulence

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Zonal flow damping

Recent global gyrokinetic simulations [1] have shown the importance of the zonal ($n = 0$, $m = 0$) component of the perturbation on ITG turbulence: while the steady (zonal flow) component is efficient in reducing turbulence, an oscillatory component at the Geodesic Acoustic Mode (GAM) frequency appears to be correlated with less efficient turbulence suppression. In this paper we examine geometrical effects on steady zonal flows and GAM oscillations. The initial zonal flow component ($n = 0, m = 0$) of an electrostatic perturbation is found to linearly damp and a residual flow level is found [2]. Therefore, we expect the $E \times B$ velocity [v_E, normalized to the initial value $v_E(0)$], generated by a pure axisymmetric density perturbation, to behave as:

$$\frac{v_E}{v_E(0)} = (1 - A_R)\, e^{-\gamma_G t} \cos(\omega_G t) + A_R \qquad ; \qquad A_R = \frac{1}{1 + 1.6 q_s^2 \,(r/R)^{-1/2}} \tag{1}$$

where A_R is the residual, at the radial position r [2]. The other parameters are R the major radius and q_s the safety factor value. The frequency and the decaying rate of the velocity perturbation are respectively:

$$\omega_G = \frac{v_{ti}}{R} \qquad ; \qquad \gamma_G = \omega_G \exp(-q_s^2) \tag{2}$$

A more accurate calculation [3], in the fluid limit, gives:

$$\omega_G = \left(1 + \frac{1}{2q_s^2}\right)^{1/2} \sqrt{\frac{2\gamma P}{\rho_m R^2}} \qquad ; \qquad \gamma_G = \omega_G \exp(-q_s^2 - \frac{1}{2}) \tag{3}$$

where γ is the adiabatic index or ratio of specific heats, P is the total plasma pressure and ρ_m is the mass density. We make the substitution $\sqrt{\gamma P/\rho_m} = c_s$, as in [4]. Here c_s is the sound speed. A kinetic expression for the frequency and the growth rate is derived in [5]:

$$\omega_G = \left(\frac{7}{4} + \tau\right)^{1/2} \frac{v_{ti}}{\sqrt{2}R} \qquad ; \qquad \gamma_G = \omega_G \exp\left[-\frac{q_s^2}{2}\left(\frac{7}{4} + \tau\right)\right] \tag{4}$$

Here τ is the ratio of the electron temperature over the ion temperature and $v_{ti} \equiv \sqrt{2\frac{k_B T_i}{mi}}$ the ion thermal velocity. One of the main differences between the fluid and the kinetic results is that the fluid expression for the frequency includes effects of the parallel dynamics, which is neglected in the kinetic calculation. Geometrical effects, such as the plasma elongation and triangularity, are ruled out in both cases by the circular magnetic surface assumption. We investigate the role of the parallel dynamics and of the plasma elongation with the electrostatic global gyrokinetic code ORB5 (details on the model can be found in [1][6]). A zonal flow damping test has been performed with the ORB5 in linear mode, which means that nonlinear terms in particle trajectory equations have been suppressed. In order to reproduce the results of Hinton and Rosenbluth theory, we solve only for the $n = 0, m = 0$ component of the electrostatic potential, the other modes are Fourier filtered. The initial condition has been prepared in order to obtain an axisymmetric ion density perturbation. The perturbation of the ion density has been set to $\delta n_i = n_0 \sin(\pi\rho)$, where δn_0 is chosen so that $\langle v_E \rangle_\rho (t = 0) = 0.07\ v_{ti}$.

Role of the parallel dynamics

A $\beta \sim 0$, circular concentric magnetic surfaces, large aspect ratio $(R/a = 10)$ equilibrium has been supplied by the ideal MHD equilibrium solver code CHEASE. The physical parameters are: major radius $R = 5$ m, minor radius $a = 0.5$ m, magnetic field on axis $B_0 = 1.44$ T. Density, ion and electron temperature profiles are flat with $T_i = T_e$. The size of the system is fixed by $L_x \equiv 2a/\rho_s = 80$, where ρ_s is the ion Larmor radius. Two cases (a) and (b), with different safety factor profiles, have been used for the test. The q_s values at the radial positions $(\rho = r/a)$ chosen for the test are:

$$\begin{array}{ccc} & \rho = 0.5 & \rho = 0.7 \\ \text{(a)} & 1.15 & 1.33 \\ \text{(b)} & 1.70 & 1.96 \end{array} \qquad (5)$$

The results of the ORB5 simulations are plotted in Fig. 1. In these figures we plot the $E \times B$ velocity normalized at the initial value $v_E/v_E(0)$ as a function of time. Time is normalized to the ion cyclotron frequency Ω_{ci}. As a reference we also plotted the residual evaluated from Eq. (1) and the exponential decay predicted by Eq. (**??**). In all cases the results are in good agreement with the residual predicted by Rosenbluth-Hinton.

Table 6 and 7 give a summary of the frequencies ω_G and decaying rates γ_G from the simulations, compared to the values predicted by theory. We find an overall good agreement between numerical results and theory predicted values. The simulations highlight the ef-

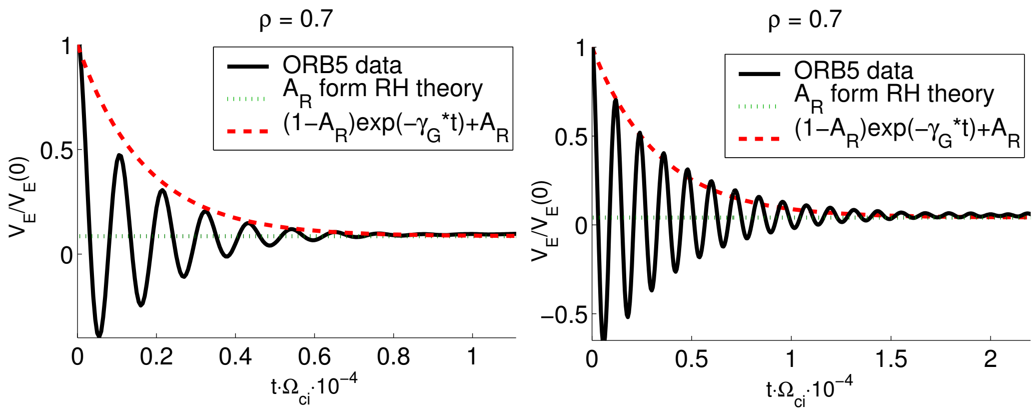

Figure 1: $E \times B$ velocity (v_E) at $\rho = 0.7$ as a function of time, for low q_s profile (a) and high q_s profile (b). The solid line is the result of the ORB5 simulation in linear mode, with $\sin(\pi\rho)$ perturbation. The dotted line is the residual and the dashed line is the exponential decay from Rosenbluth-Hinton theory.

fect of the parallel dynamics on ω_G which is correctly included in the fluid model, [Eq. (3)], but not in the kinetic model, [Eq. (4)], where the q_s dependence has been neglected.

q_s	ω_G Eq. (4)	ω_G Eq. (3)	ω_G (ORB5)
1.15	0.0059	0.0059	0.0061
1.33	0.0059	0.0057	0.0058
1.70	0.0059	0.0055	0.0053
1.96	0.0059	0.0054	0.0053

(6)

q_s	γ_G Eq. (4)	γ_G Eq. (3)	γ_G (ORB5)
1.15	-0.0010	-0.0010	-0.0009
1.33	-0.0005	-0.0006	-0.0006
1.70	-0.0001	-0.0002	-0.0002
1.96	-0.00002	-0.0001	-0.0001

(7)

Role of the plasma geometry

In order to investigate the role of plasma elongation, we run a simulation with the same parameters as in the previous section [safety factor profile (a)], but with an elongation $\kappa = 1.5$. The resulting frequency, growth rate and residual are noted in Table 8:

$\kappa = 1.5$	ω_G (ORB5)	γ_G (ORB5)	A_R (ORB5)
$q_s = 1.15$	0.0060	-0.0008	0.109
$q_s = 1.33$	0.0058	-0.0007	0.098

(8)

Comparing these results with the ones in Table 6 and 7, we observe that the elongation alone has a minor effect on the frequency and damping rate. Now we introduce a more complex magnetic configuration which is reconstructed from a shot of the tokamak TCV. It is a D-shaped plasma with inverse aspect ratio $\epsilon \equiv a/R = 0.27$, $a = 0.24$ m $= 40\ \rho_i$, triangularity $\delta = 0.4$ and magnetic field on axis $B_0 = 1.44$ T. Density, ion temperature and electron temperature profile are flat with $T_i = T_e$. The size of the system is fixed by $L_x \equiv 2a/\rho_s = 80$, where ρ_s is the ion Larmor radius. Two different values of the plasma elongation are considered $\kappa = 1$ and $\kappa = 1.5$. The q_s values at the radial positions chosen for the test are $q_s(\rho = 0.5) = 2.20$, $q_s(\rho = 0.7) = 3.10$. The results are noted in Table 9 and 10:

$\kappa = 1$	ω_G (ORB5)	γ_G (ORB5)	A_R (ORB5)
$q_s = 2.2$	0.0140	−0.0012	0.049
$q_s = 3.1$	0.0138	−0.0011	0.035

(9)

$\kappa = 1.5$	ω_G (ORB5)	γ_G (ORB5)	A_R (ORB5)
$q_s = 2.2$	0.0128	−0.0013	0.058
$q_s = 3.1$	0.0124	−0.0012	0.042

(10)

For the case $\kappa = 1$, we write in Table 11 the values predicted by the kinetic and fluid theories. A comparison between Table 11 and Table 9 shows that triangularity and small aspect ratio effects introduce a substantial difference between the predicted γ_G values and the values obtained by the simulations. Again, comparing Table 9 with Table 10 gives us an idea of the magnitude of the elongation effects.

$\kappa = 1$	ω_G Eq. (4)	γ_G Eq. (4)	ω_G Eq. (3)	γ_G Eq. (3)	A_R Eq. (1)
$q_s = 2.2$	0.0149	$-7 \cdot 10^{-5}$	0.0167	$-2 \cdot 10^{-5}$	0.046
$q_s = 3.1$	0.0146	$-6 \cdot 10^{-7}$	0.0167	$-3 \cdot 10^{-8}$	0.028

(11)

The preliminary results presented suggest that geometrical effects can play a relevant role on the physics of the zonal flow damping. The effects from the triangularity and aspect ratio together seem to be more important than from the elongation only. Further investigations are needed in order to separate the effects of triangularity and aspect ratio.

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