A new mechanism causing strong decay of geodesic acoustic modes: combined action of phase-mixing and Landau damping

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Introduction

A new mechanism able to damp very efficiently the geodesic acoustic mode (GAM) in the presence of a non-uniform temperature profile is identified. First, we briefly introduce the framework within which this mechanism is expected to be relevant. A fundamental question in tokamak physics is the understanding of the suppression mechanism of turbulent transport. Experimental and simulation results suggest the saturation of turbulence to be mediated by the self-generated zonal flows. These are characterized by a velocity shear flow that reduces the radial correlation length of turbulence structures and the associated transport. Several theoretical models have been proposed in order to explain the formation of zonal flows [1, 2, 3]. Due to the presence of geodesic curvature in toroidal devices, the zonal flows contain particular oscillations called GAMs [4]. These oscillations play a very important role in regulating the efficiency of zonal flows with respect to the suppression of turbulence. The GAM can transfer energy from the electric field of the zonal flows to pressure perturbations linked to the turbulence. In this way, the level of zonal flows becomes low enough that turbulence is not fully suppressed [5, 6]. In tokamak plasmas, GAMs are subject to Landau damping by the passing ions. Moreover, due to the local GAM frequency dependence on the plasma parameters, such as temperature, a continuum spectrum of GAM exists in tokamak plasmas, where the temperature varies across the magnetic flux surfaces. As a consequence, a GAM is affected by phase-mixing [7, 8]. The effect of the phase-mixing is to modify the radial structure of the perturbation, with a energy cascade from low to high radial wave numbers [7]. Here we describe how phase-mixing and Landau damping can act at the same time, with a combined action resulting in a strong damping mechanism for GAM. This represents a particular case of a general mechanism, that we have found, and that can be observed whenever the phase-mixing acts in the presence of a damping effect that depends on the wave number k_r. The general mechanism, which we call *Phase-mixing Damping Adjustment* (PDA), can play a very important role not only in the plasma fusion domain, but also in other physical contexts. The validity of this new GAM damping mechanism is derived analytically and investigated numerically. Details can be found in Ref. [9].

Model and Simulations

In this work we use the numerical gyrokinetic code ORB5 [10], which now includes all extensions made in the NEMORB project [11]. The ORB5 code uses a Lagrangian formulation based on the gyrokinetic Vlasov-Maxwell equations. The code solves the full-f gyrokinetic Vlasov equation for ions, using a particle-in-cell δf method. Electrons are treated adiabatically in this paper, yet they can also be treat drift-kinetically with ORB5. Energy and momentum conservations can be proved via gyrokinetic field theory. To obtain the potential ϕ, the Vlasov equation must be coupled to the quasi-neutrality condition. In the code, time t is normalized to the inverse of the ion cyclotron frequency $\Omega_i = eB_0/m_i$, the radial direction is normalized to $\rho_s = \sqrt{k_B T_{e,0} m_i}/(eB_0)$ in which $T_{e,0}$ is the electron temperature, and the potential is given in $\phi_0 = k_B T_{e,0}/e$ units. The quantity B_0 is calculated in the axial radial position, and $T_{e,0}$ is calculated in the middle of the radial domain. The ion Larmor radius is defined as $\rho_i = \sqrt{2}\sqrt{T_{i,0}/T_{e,0}}\rho_s$ where $T_{i,0}$ is the ion temperature. We assume $\tau_e = T_e/T_i = 1$ in all the simulations. With this model, we first investigate the Landau damping rate γ of GAMs as a function of several parameters, such as the safety factor q and the radial wave number k_r associated to these structures. To this purpose, we initialize a sinusoidal potential perturbation independent of poloidal and toroidal angles along the minor radius a. The perturbation evolves in a linear electrostatic collisionless simulation. We choose a tokamak with an inverse aspect ratio $\varepsilon = a/R_0 = 0.1$. We assume a flat safety factor profile. Temperature and density profiles are first also considered flat and the diameter $L_r = 2/\rho^* = 320$, with $\rho^* = \rho_s/a$. In this way we can compare the results of the ORB5 simulations with the analytical prediction of the theory of Sugama-Watanabe in which finite orbit width (FOW) effects are included to the first order [12, 13]. For other benchmark see Ref. [14]. The reference simulation has a spatial grid of $(r \times \theta \times \phi) = (256 \times 64 \times 4)$ and a time step of $100\ \Omega_i^{-1}$. The results are summarized in Fig. 1 that shows the damping rate γ as a function of $k_r\rho_i$ for several values of the safety factor q. We emphasize that for $q > 1$, the damping rate strongly increases with $k_r\rho_i$. We find a good agreement between theory and simulations.

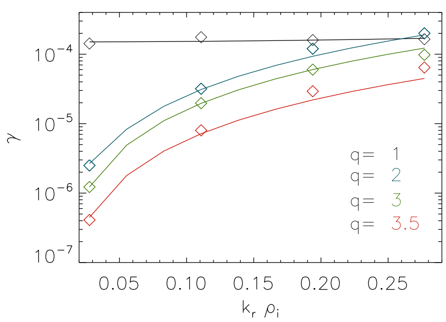

Figure 1: *Damping rate γ as a function of wavenumber k_r. Results of simulations (points) agree with theory (continuous lines).*

Now, we discuss linear simulations considering a GAM decay that evolves in the plasma equilibrium close to that measured at the edge of ASDEX Upgrade in the discharge 20787 [15]. Considering values measured in this plasma around the radial position $\rho_{pol} \approx 0.92$ and considering hydrogen mass, we obtain the following quantities: $\Omega_i = 1.9 \cdot 10^8\ rad/s$, $\rho_i = 9.7 \cdot 10^{-4}\ m$ and an ion thermal velocity $v_{thi} = \sqrt{2k_B T_i/m_i} = 1.8 \cdot 10^5\ m/s$. Using these parameters as inputs, we perform simulations with $L_r = 1441$ and $\varepsilon = 0.3$. We assume a flat q-profile with $q = 3.5$ and a flat density profile. These assumptions will be discussed later. We initialize a potential perturbation with a radial gaussian profile whose width is $k_r\rho_i \approx 0.12$. Simulations have a spatial grid of $(r, \theta, \phi) = (1024 \times 64 \times 4)$ and a time step of $50\ \Omega_i^{-1}$. In order to investigate the effects of a temperature gradient, by means of a hyperbolic tangent, we consider two profiles of temperature

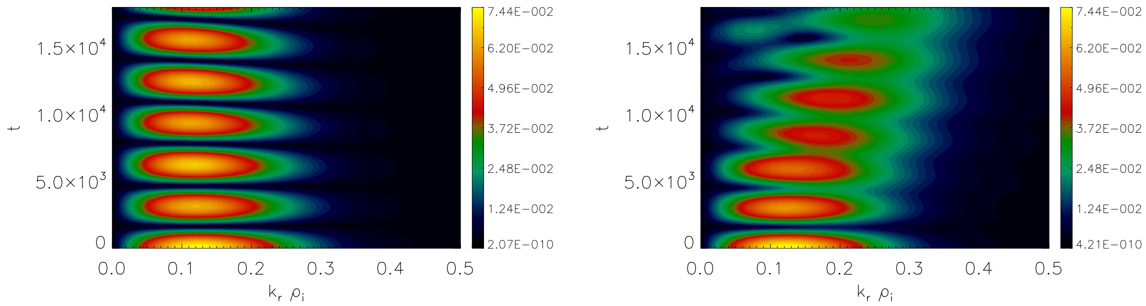

Figure 2: *Time evolution of k_r modes of E_r in the plane (k_r,t) for $ak_T = 0$ (left) and for $ak_T = 7$ (right).*

with the following gradients $ak_T = a\,\nabla T/T = 0$ (with T electron/ion temperature) and $ak_T = 7$ in the middle of the radial domain. The results are shown in Fig. 2. For the case $k_T = 0$ (left panel) we find in the plane (k_r,t) several oscillations of GAM with the k_r amplitude that decreases in time due to Landau damping. We note that the k_r range is constant in time. In the case of a nonuniform temperature profile, due to the continuum spectrum described by $\omega_G(r) \propto \sqrt{T}$ the perturbed electric field oscillates at each radial position with the local GAM continuum frequency, $\delta E_r(r,t) = A_1 e^{-i\omega_G(r)t}$. The initial perturbations will generate finer radial structures with high k_r numbers by phase-mixing. This mechanism does not imply a dissipation of energy. In fact, the energy linked to electric field is proportional to $|\delta E_r|^2$. If we approximate locally the continuous spectrum as $\omega_G(r) = \alpha + \beta r$ with $\beta \propto k_T$, the spatial Fourier transform $\delta\tilde{E}_r$ of the perturbed electric field is given by $\delta\tilde{E}_r = 2A_1 e^{-i\alpha t}\lim_{c\to\infty}\sin[(\beta t + k_r)c]/(\beta t + k_r)|_{-c}^{+c}$. This shows that with increasing time, energy is increasingly shifted towards high k_r numbers. This is clearly observed in Fig. 2 (right panel). However, we note that the amplitude of the modes decreases faster with respect to the case $k_T = 0$. This is due to the fact that, as we have shown in Fig. 1, the Landau damping is very efficient for high k_r. In order to quantify this combined action of phase-mixing and Landau damping we note that we have considered a range for q and for k_r for which the theory of Sugama-Watanabe is a good approximation. To this purpose, we consider the Landau damping rate $\gamma = -f + k_{r0}^2\, g$ for a GAM with a fixed radial wave number k_{r0}. The f and g expressions can be found in Eq. 3 of Ref. [13]. Considering that in the presence of a continuum spectrum the radial wave number k_r is shifted in time with $k_r = (k_{r0} + \beta t)$, we can write the damping rate due to the combined action of Phase-mixing and Landau (PL) damping as $\gamma_{PL}(t,k_T) = -f(v_{T_i},q,\tau_e) + (k_{r0} + \beta t)^2 g(v_{T_i},q,\tau_e)$. The evolution of the electric field is described at each time by:

$$\gamma_{PL}(t,k_T) = (1/E_r)(\partial E_r/\partial t) \qquad (1)$$

Eq. 1 is solved with an initial-value code in order to calculate the evolution in time of the GAM electric field. This analytical evolution is then compared with the results of ORB5 simulations. In Fig. 3 we show the electric field at the middle of the radial domain as a function of time t in Ω_i^{-1} units. We observe that the envelope $E_r(t)$ given by Eq. 1 evolves in agreement with the electric field numerically obtained for the case $ak_T = 7$. For these simulations we have considered the previous parameter values based on the discharge 20787, with a monochromatic signal with $k_r \rho_i = 0.061$ and $q = 3$.

The theory well describes the strong damping with respect to the case $k_T = 0$ in which only Landau damping acts. It is important to note that simulations performed with a non-zero density gradient give results very close to the simulations performed with a flat density profile. This is in agreement with Eq. 1 which does not depends on the density gradient. Moreover, we note that γ_{PL} in Eq. 1 depends also on q. However, the gradient of q has a weak influence on the phase-mixing and consequently on γ_{PL}. We have verified this aspect by numerical simulations.

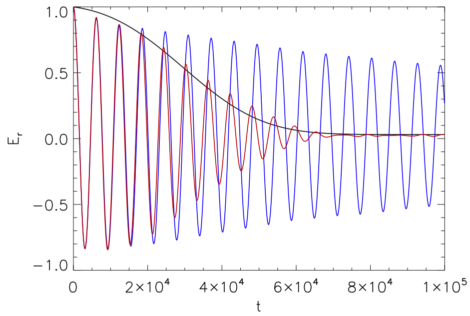

Figure 3: *E_r in middle of radial domain vs time for $ak_T = 0$ (blue), for $ak_T = 7$ (red). The black line is E_r envelope from Eq. 1 for $ak_T = 7$.*

Conclusions

In this paper we have presented how the combined actions of phase-mixing and Landau damping generate a novel mechanism able to damp very efficiently GAM oscillations in the presence of a strong temperature gradient. This mechanism can play an important role in regulating energy transport in tokamak and in particular can play a role in the dynamics of the L-H mode confinement. The *PL* damping mechanism could be one of the reason for the suppression of GAM oscillations in the H-mode regime in which a strong temperature gradient is observed at the edge of the plasma [9].

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