Gyrokinetic modelling of anisotropic energetic particle driven instabilities in tokamak plasmas

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Introduction

The geodesic acoustic mode (GAM) can be excited by energetic particles (EPs) via inverse Landau damping, generating an energetic-particle driven GAM or EGAM (1). The study of such mode is of interest since it provides an additional mean of power exchange between the energetic and the bulk ions (2) and it can be used to regulate turbulence. It has been shown that anisotropy in velocity space is necessary for the linear excitation of the mode (3). In particular, positive gradients of the distribution functions in velocity space ($\partial f/\partial \varepsilon > 0$) are needed to drive EGAMs, and as a consequence of which a certain portion of EPs will be redistributed to lower energies. In previous work, analytical anisotropic distribution functions are bump-on-tail (2) and slowing down with pitch dependency (1). The aim of this paper is studying the effects of realistic anisotropic distribution functions on the linear growth of EGAMs in order to obtain fully predictive simulations of experimental scenarios. For this paper the global, gyrokinetic, PIC code ORB5 (4) is run linearly and electrostatically. For the purposes of this paper a new analytical distribution function is formulated and implemented in the gyrokinetic code ORB5. The numerical results and the effects of the shape of the distribution function in velocity space, in terms of its parameters, are reported and discussed. Furthermore, experimental relevant distributions functions from Fokker-Planck solver code RABBIT (5) are presented and later used to obtain realistic simulations of NLED-AUG case (6) with experimental density and temperature profiles. Results are qualitatively compared with NLED-AUG case experimental data and then discussed.

Analytical slowing down and results

A new analytical slowing down distribution function with pitch angle dependency was implemented in ORB5. The particular anisotropic shape chosen for this distribution is meant to imitate analytically with two parameters the anisotropy presented by experimental-like EP distribution functions obtained from NBI beams simulated through the Fokker-Planck solver RAB-

BIT. Such parameters are: the pitch angle of the particle $\xi = v_{\|}/|v|$ and a standard deviation σ_ξ characteristic of the focus of particles along the preferred pitch angle (ξ_0).

$$f(v,\xi,\psi) = \frac{2\sqrt{\frac{2}{\pi}}}{\sigma_\xi[erf(\frac{\xi_0+1}{\sqrt{2}\sigma_\xi}) - erf(\frac{\xi_0-1}{\sqrt{2}\sigma_\xi})]} \exp(-\frac{(\xi-\xi_0)^2}{2\sigma_\xi^2}) \frac{0.75\ \Theta(v_\alpha - v) n_{val}(\psi)}{\pi(v_c^3+v^3)} ln(1+(\frac{v_\alpha}{v_c})^3)$$

Where $n_{val}(\psi)$ is the normalized density at a given radius, v_α is the injection velocity of the particles and v_c is the critical velocity. This distribution function is essentially the superimposition of a slowing down in energy characterized by v_α and v_c and an anisotropic gaussian in parallel velocity characterized by the two parameters σ_ξ and ξ_0.

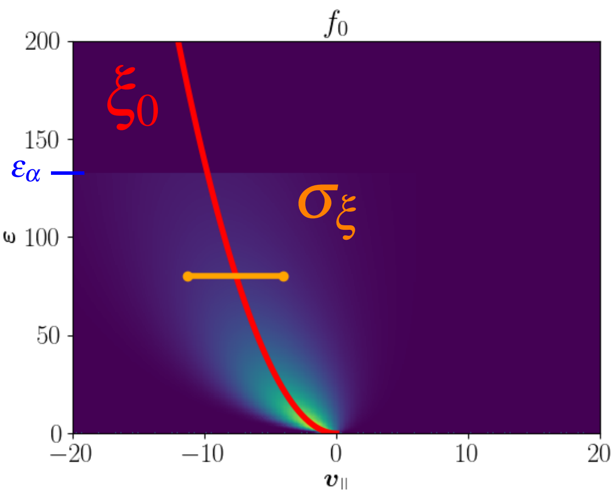

Figure 1: Analytical slowing down with pitch angle dependency, ξ_0 and σ_ξ are qualitatively represented in the f_0 plot

The purpose of this distribution function is to study the effects of anisotrpy through two simple parameters. For higher energies, where the isotropization effect shown in RABBIT distribution functions is low, the RABBIT numerical distribution functions can be fitted through a gaussian which resembles the anisotropic structure in parallel velocity of the analytical distribution function. A scan of this distribution functions was run linearly and electrostatically varying ξ_0 between 0 (particles mostly trapped) and -1 (particles mostly deep passing) and σ_ξ between 0.1 (particles concentrated along a single pitch, very anisotropic) and 0.6 (particles with broader distribution in parallel velocity, almost isotropic). The results of the simulations are displayed in Figure 2. **Effects of σ_ξ**: the growth rate is found to be decreasing, eventually yielding negative values, as $\sigma_\xi \longrightarrow \infty$. Such behaviour was expected in literature, since it was found that anisotropy is needed to excite linearly EGAMs. In general EGAMs are excited for $\sigma_\xi \in (0.1, 0.5)$. It can be observed that the highest growth rate is found for higher σ_ξ as ξ_0 increases, this is due to the change of position of the positive gradients in the distribution functions with respect to the resonant velocity.

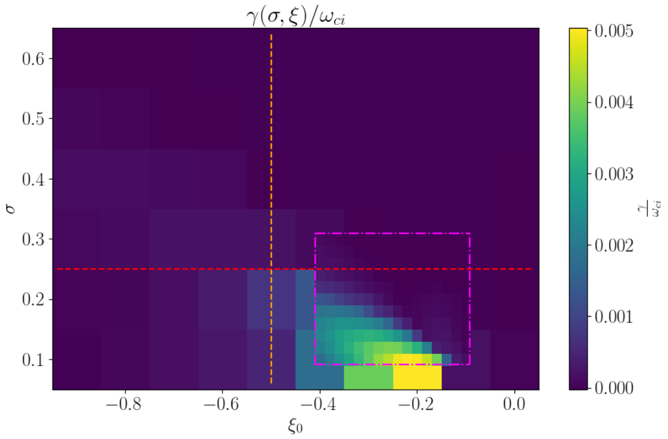

Figure 2: Growth rate (γ/ω_{ci}) of EGAMs as function of ξ_0 and σ_ξ

Effects of ξ_0: as ξ_0 moves from 0 to -1 the growth rate is found to be increasing till a maximum located between -0.3 and -0.8 (as mentioned above, depending on σ_ξ), after that it declines again till the other extreme -1. The modes are rather stable near the extremes 0 and -1. This is also somehow expected from the theory. In fact, trapped particles ($\xi = 0$) are unable to interact with the resonant velocity of the mode and deeply passing particles ($\xi = -1$) also are too fast to exchange energy with the mode via inverse Landau damping. Therefore the maximum growth rate is found for mid values of ξ_0 when a positive gradient in the distribution function is found at the resonant velocity.

Once we gained some basic knowledge about the behavior of EGAM's growth rate according to how anisotrpy in shaped in phase space we can move our attention to the results obtained by feeding as input into ORB5 a numerical experimental-like distribution function obtained from RABBIT.

RABBIT distribution function and results

The experimental-like distribution functions were obtained from RABBIT for the four shots #31213-6 of NLED-AUG case, simulations were run using realistic equilibrium and profiles from the same shots. The differences in the shots regard the angle with which the NBI were oriented to produce the EP populations. In shot #31213 the NBI had an angle of 7.15° with respect to the magnetic axis, in shot #31214 6.05° and in shots #21315-6 6.65°. As a result, higher angles correspond to more off-axis EP profiles and distribution functions with lower pitch angles (closer to the mid-range values of ξ_0, where higher growth rates are yielded, as mentioned above). Linear electrostatic simulations with RABBIT experimental-like f_0 yield damped modes in all four cases at nominal EP density $\left\langle \frac{n_{EP}}{n_e} \right\rangle = 0.095$. EP density threshold were found for the three different pitch angles in order to evaluate the most unstable case. For shot #31213 $n_{EP,thr} \simeq 23\%$, for #21216 $n_{EP,thr} \simeq 27\%$ and for #21214 $n_{EP,thr} \simeq 32\%$. Such results match the expectations found above in the analytical scan. In fact, being the RABBIT f_0 gaussian fit close to the analytical case with $\xi_0 \simeq 0.85$ and $\sigma_\xi \simeq 0.2$, we expect the most unstable mode to be that with lower pitch angle, namely shot #31213, and the most stable that with the higher pitch angles, namely #31214. The threshold values found above prove this result.

Nevertheless, the growth rates yielded from linear simulations at nominal EP density using RABBIT distribution functions are in disagreements both with the results from the analytical cases that best fit the RABBIT distribution functions, which yield slightly positive growth rates at nominal density, and with experimental measurements, presented in Figure 3, which show growing EGAMs bands just below 50kHz.

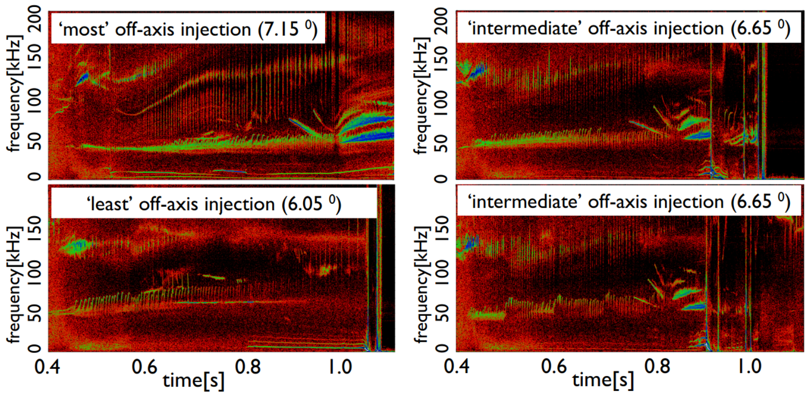

Figure 3: Experimental data from NLED-AUG case from magnetic pick-up coils (in order top-left, top-right, bottom-left, bottom-right: 31213,5,4,6)

The first mismatch could be explained with the jumps in energy presented in RABBIT f_0. Typically NBIs present three injection velocities: E, $E/2$ and $E/3$. As a result, the distribution functions obtained from such NBIs will present really steep negative gradients in energy in correspondence of the injection velocities. RABBIT may overestimate such gradients, therefore the damping effect may be less in experiments. It was observed that such gradients damp strongly the mode overcoming the driving effects of the positive gradients in velocity. Apart from uncertainties in q that are well known to change the EGAM damping rates, the second mismatch is hypotesized to be due to the incomplete physics used to run the simulations. In fact, electrostatic linear simulations lack all the non-linearities and electro-magnetic effects which may account for this differences between measurements and linear electrostatic simulations. In particular we expect the n=1 Alfvén Wave to non-linearly drive the EGAM unstable as described in (7). Work is undergoing to prove this hypothesis.

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