Gyrokinetic investigation of the nonlinear interaction of Alfvén instabilities and energetic-particle driven geodesic acoustic modes

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Next generation fusion devices (ITER [1], DEMO [2]) will be characterized by a significant population of energetic particles (EPs) that, to successfully achieve ignition, have to be confined for long enough times. However, EPs can drive instabilities through resonant wave-particle interaction. Among these, the Alfvén modes [3] (Alfvén eigenmodes, AE and energetic particle driven modes, EPM) can redistribute the EPs in phase-space leading to a less effective heating and to a possible damage of the first wall. The energetic particle driven geodesic acoustic modes (EGAM) instead can be used to regulate turbulence [4] and can provide an additional energy exchange mechanism between EPs and thermal plasma [5]. The so-called “NLED-AUG case” [6] represents a unique scenario for the study of the EP physics since it has been obtained by tuning the plasma parameters such that the ratios $\beta_{EP}/\beta_{plasma} \simeq 0.2-1$, $\mathcal{E}_{EP}/T_{plasma} \simeq 150$ are comparable to those expected in future fusion reactors. Through this choice the effects of the background plasma (turbulence) are minimized and the rich nonlinear physics observed (like the interaction of TAE-EPM bursts and EGAMs) is dominated by the presence of the EPs. In this paper we employ the global, nonlinear, electromagnetic, gyrokinetic, PIC code ORB5 [7] to study the interaction between AEs and EGAM, using plasma parameters inspired by the NLED-AUG scenario quoted above, extending the studies presented in Ref.[8, 9]. Only the EPs follow their full trajectories, while thermal particles are pushed along their unperturbed orbits.

AE-EGAM interaction mediated by EPs

The EPs are modelled via a double-bump-on-tail distribution function with a radial density gradient, while the background species have Maxwellian distribution functions. Given the complexity of the problem under investigation we simplify at first the scenario considering the radial density profiles of the NLED-AUG case but a magnetic equilibrium with circular surfaces. Additionally the EPs have an on-axis radial density profile. The results of simulations obtained in a scan against the EP concentration have been discussed in Ref.[10]. There the dynamics observed in single-toroidal mode simulations ($n = \{0\}$ only for the EGAM and $n = \{1\}$ only for the AE) has been compared with that observed in two-toroidal mode simulations $n = \{0,1\}$ where the AE and what we call now more generally zonal structure (ZS) are observed to interact. At high EP concentration, where the AE is more unstable than the EGAM, the forced driven excitation [11] has been recognized, in two-toroidal mode simulation, as the mechanism responsible of the drive of the ZS. On the other hand, at low EP concentration new and surprising results have been obtained (see Fig.1). The EGAM, being now the most unstable mode, when interacting with the AE drives the latter, modifying its dynamics respect to what observed in simulations with $n = \{1\}$ only. These results have been explained with a new theoretical model obtained following the arguments proposed in Ref.[11]. There, the observed mode interaction was explained in terms of three wave coupling mediated by the curvature-pressure coupling term of the EPs (the background plasma contribution being negligible in the experiments and not included in the simulations). We have extended the theory there proposed considering the case of a general AE pumped by an EGAM and the theoretical estimates have been found in good agreement with the simulation results [10]. The developed analytical theory has been used to justify the results found in simulations where the ASDEX Upgrade equilibrium

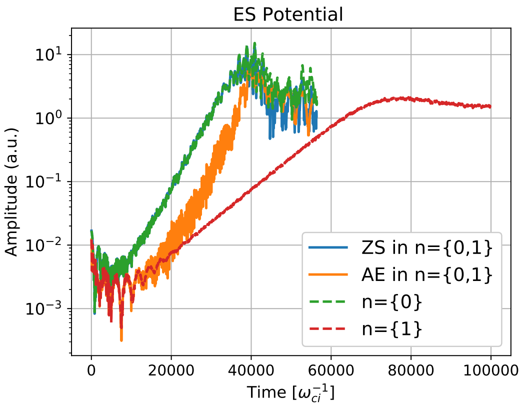

Figure 1: *Temporal dynamics observed in simulations at low EP concentration.*

has been considered and the EPs have an off-axis radial density profile (as modelled by TRANSP [12]). Even in this case, in fact, two regimes have been observed. At low EPs concentration, $\langle n_{EP}\rangle/\langle n_e\rangle < 0.09$ the EGAM drives the AE, while at higher concentrations the opposite situation happens. In Fig.2 we measure, in a scan against the EP concentration, the ratio of the AE saturation level in presence and in absence of the EGAM. From the scan, it results that this ratio is higher in the regime where the EGAM is stronger.

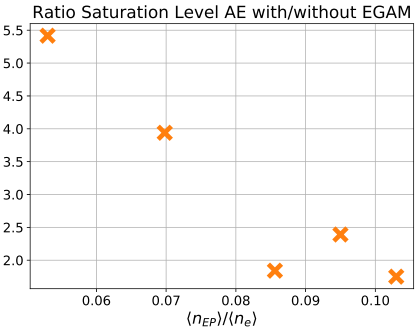

Figure 2: *Modification of the saturation level of the AE, in presence of an EGAM*

Implementation of the Slowing-Down distribution function

The need to go closer to the experimental conditions to fully understand the physics behind the experiment requires to perform simulations with a more realistic distribution function. To this purpose, an analytical slowing-down distribution function [13] has been successfully implemented in ORB5:

$$f_{0,EP} = \frac{n_{EP}}{\frac{4\pi}{3}\log\left[1+\left(\frac{v_{EP}}{v_c}\right)^3\right]}\frac{\theta(v_{EP}-v)}{v_c^3+v^3} \quad , \quad v_c = v_{th,e}\left(\frac{3\sqrt{\pi}}{4}\frac{m_e}{n_e}\sum_{j=bulk\ ions}\frac{n_j z_j^2}{m_j}\right)^{\frac{1}{3}} \tag{1}$$

where the “crossover velocity” v_c together with the “EP birth speed” v_{EP}, linked to the EP injection energy $\mathcal{E}_{EP}$, appear ($v_{EP} = \sqrt{2\mathcal{E}_{EP}/m_{EP}}$). In Eq.1, $v_{th,e}$, m_e and n_e are respectively the thermal velocity, mass and density profile of the electrons. n_j, m_j and z_j are respectively the density, mass and atomic number of the ions of the background plasma. In Fig.3 a portion of the distribution function at fixed radial position $s \approx 0.5$ and $\mu = 0$ is shown. There we observe the cut in the parallel velocity of the distribution function in normalized ORB5-units. This value corresponds to an injection energy of $\mathcal{E} \simeq 93keV$ that is the energy of the neutral beam injected in the machine to obtain the NLED-AUG case. Simulations are in progress with the use of this new implemented distribution function. We discuss here the results observed in a single toroidal mode simulation $n = \{1\}$, where the EPs have an off-axis radial density profile at the reference experimental concentration $\langle n_{EP}\rangle/\langle n_e\rangle = 0.0949$ (see Ref.[6]). The thermal species have Maxwellian distribution function. In its growing exponential phase the mode structure of the electrostatic potential is peaked around $s \approx 0.2$ and is dominated by its Fourier component $(m,n) = (2,1)$. The measured frequency in this temporal range is $f = 105\,kHz$. It lies below the continuum spectrum (see for comparison the red curve in Fig.4, representing the continuum spectrum calculated with LIGKA [14]). In Fig.4 the frequency spectrum calculated in the nonlinear phase is shown. We observe the measured frequencies to lie in the range $106\,kHz \leq f \leq 146\,kHz$. Additionally it is interesting to notice that the TAE frequency begins to appear, lying in the gap created between the two branches of the continuum (at $s \approx 0.73$).

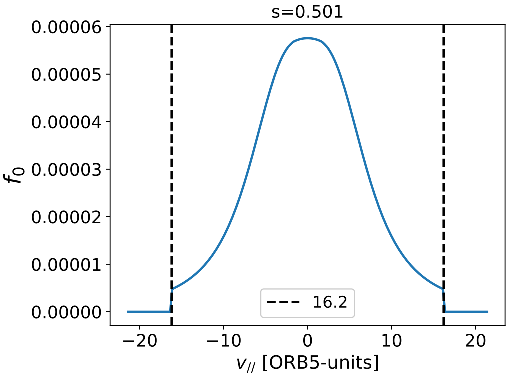

Figure 3: *Shape of the slowing-down distribution function in $v_\parallel$ space ($\mu = 0$ and $s \approx 0.5$).*

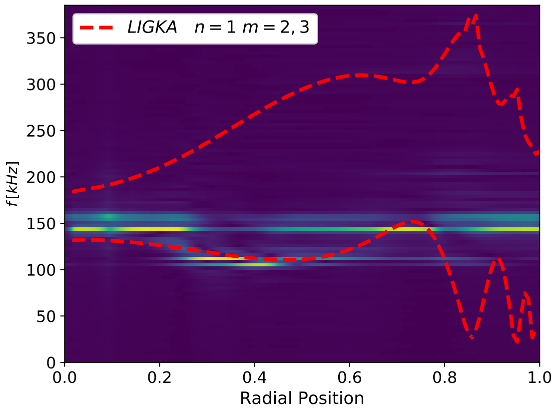

Figure 4: *Frequency spectrum observed in the non-linear phase with a slowing down EP distribution function.*

The observed mode frequencies result in good agreement with the experiments. The results exposed in these sections show that ORB5 is able to catch the nonlinear physics present in the experiments and it is an important tool to predict the driven EPs dynamics that is going to be met in future generations fusion machines. Naturally the choice of the distribution function represents one of the main approximations done in the performed simulations. Through the new implemented slowing-down distribution function we are able to go closer to the experimental set providing results that represent an important starting point to understand the physics acting below the experiment. Also, the new implemented slowing-down distribution has the possibility to include the presence of an anisotropy in velocity space that can drive unstable EGAM. Future works will detail the dynamics observed using this new distribution function and further investigation of the interaction between the observed AE and the EGAM will be performed. Finally, it will be important to study and understand the mode dynamics when also the background plasma particles are allowed to follow their full trajectories (extending the presented results to a self consistent model including background turbulence).

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