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Theory and simulation of low-frequency drift Alfvén waves in toroidal fusion plasmas

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We present an overview of theory and simulation of low-frequency drift Alfvén waves (DAW) in toroidal fusion plasmas based on the framework of the general fishbone like dispersion relation (GFLDR) [1, 2, 3]. In addition to recovering various limits of the kinetic MHD energy principle, this approach can also be applied to general e.m. fluctuations characterized by a broad range of spatial and temporal scales consistent with gyrokinetic descriptions of both core and supra-thermal plasma components. Therefore, the GFLDR provides a unified description of DAW excited by energetic particles (EPs) as either Alfvén eigenmodes (AEs) or energetic particle modes (EPMs). Furthermore, the GFLDR is given in the following generally variational integral functional form

$$2\pi^2 \int_0^a dr \left[\frac{k_\vartheta^2 c^2 (d\psi/dr)}{calJB_0^2}\right]_{\vartheta=0} |A(r)|^2 \left[\delta\bar{W}_f(r) + \delta\bar{W}_k(r) - i\lambda(r)\right] = 0 \ . \qquad (1)$$

For radially localized fluctuations, the GFLDR can then be written as

$$i\lambda(r) = \delta\bar{W}_f(r) + \delta\bar{W}_k(r) \ , \qquad (2)$$

where Λ represents a generalized inertia, while $\delta\bar{W}_f$ and $\delta\bar{W}_k$ describe the potential energy of the fluctuations accounting, respectively, for the fluid and kinetic plasma response [1, 2, 3]. From the structure of Eqs. (1) and (2), the present approach allows extracting spatial and temporal scales of the considered fluctuation spectrum as well as the underlying physics. For example, radial singular structures of the shear Alfvén wave (SAW) continuous spectrum are shown in FIG. 1 using the analytic as well as the numerical solution for the generalized inertia, Λ, in the MHD fluid limit [4, 5]. Meanwhile, analytic results on mode frequency, damping and finite orbit width effects can be verified numerically with very good agreement for both SAW continuum accumulation points [6, 7] as well as for geodesic acoustic mode oscillations [8]. Thus, the GFLDR as a unified theoretical framework can help understanding experimental observations as well as numerical simulation and analytic results with different levels of approximation.

The gyrokinetic analysis of low-frequency DAW is necessary for a proper description of short wavelengths and/or accounting for finite parallel electric field and wave damping as well as for EP excitations [3, 6, 7]. Here, we derive the corresponding GFLDR theoretical framework in general tokamak geometry as a joint effort of ongoing research projects [9, 10]. As first application of the general theory, we extend to gyrokinetic analysis the application to the Alfvén - acoustic fluctuation spectrum of Ref. [4] in the MHD fluid limit. This analysis, presented in detail in a dedicated contribution [11], confirms the general prediction that fluctuations with acoustic polarization are unfavored because of the stronger Landau damping and the weaker response to EPs [4], in agreement with recent observations in DIII-D [12].

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As further application, motivated again by recent experimental observations [12] consistent with earlier theoretical predictions [4], we apply the GFLDR theoretical framework to simple (s, α)-equilibrium tokamak geometry. In particular, we use the analytic expression of the generalized inertia, Λ, derived earlier for well circulating/deeply trapped thermal ions [13, 14]. Our results, presented in detail in a separate work [15], show, again, that the acoustic branch is strongly suppressed by Landau damping and that EP excitation is generally weak.

Numerical results by the Drift Alfvén Energetic Particle Stability (DAEPS) code will also be shown and discussed [10]. DAEPS belongs to a long-term project launched to better relate experimental observations and theoretical/physical understandings of DAW (AEs/EPMs) interacting with thermal plasma as well as EPs (including alpha particles). DAEPS is a gyrokinetic eigenvalue solver, which can properly represent kinetic compression and wave-particle resonances of core and energetic plasma components.

Compared to initial value codes, the DAEPS approach is a valuable method to analyze the whole stable/unstable spectrum besides the most unstable mode. As demonstration, the beta-induced AE (BAE) is used to illustrate the relevant aspects of the code.

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