Contribution ID: **820** Type: **Regular Poster**

Effects of core plasma on the low frequency Alfven and Acoustic eigenmodes

Thursday 13 May 2021 12:10 (20 minutes)

Low frequency modes belonging to the Alfvenic Kinetic Ballooning mode (KBM)[1] and the mixed polarization Beta-induced Alfven Acoustic Eigenmode (BAAE)[2] branches, have been recently observed experimentally [3] and confirmed numerically [4]. Due to the low frequency range of the core ion bounce motion, kinetic treatment of both circulating[5,6] and trapped particles[7,8] is required in order to properly describe these fluctuations. We give the dispersion relation of the aforementioned modes in the framework of the Generalized fishbone-like dispersion relation (GFLDR)[1,9]

$$i\Lambda(\omega) = \delta\bar{W}_f + \delta\bar{W}_k \ \ ,$$

which is a unifying theoretical description for various Alfvenic fluctuations, as well as Energetic particle continuum modes (EPMs). Here, Λ is the generalized inertia representing the physics on short radial scales, while $\delta\bar{W}_f$ and $\delta\bar{W}_k$ are the ideal region fluid and kinetic contribution, respectively.
We assume low $\beta = O(\epsilon^2)$ axisymmetric (s,α) plasma equilibrium and solve the vorticity equation:

$$B\mathbf{b}\cdot\nabla\left[\frac{1}{B}\frac{k_\perp{}^2}{k_\vartheta{}^2}\mathbf{b}\cdot\nabla\delta\psi\right] + \frac{\omega^2}{v_A^2}\left(1-\frac{\omega_{*pi}}{\omega}\right)\frac{k_\perp^2}{k_\vartheta^2}\delta\phi + \frac{\alpha}{q^2R^2}g(\theta)\delta\psi =$$
$$nonumber$$
$$\left\langle\frac{4\pi e}{k_\vartheta^2c^2}\omega\omega_{di}\delta K_i\right\rangle,$$

and quasi-neutrality condition, in the long wavelength limit [1,5,7]:

$$\left(1+\frac{T_i}{T_e}\right)(\delta\phi-\delta\psi) = \frac{T_i}{ne}\langle\delta K_i - \delta K_e\rangle\,.$$

Here $\langle(...)\rangle = \int d\mathbf{v}(...)$, $\delta K_{e,i}$ are the particle non-adiabatic distribution functions, $g(\theta) = \cos\theta + [s\theta - \alpha\sin\theta]\sin\theta$ and $n_e = n_i = n$. Expanding the fields $\delta\Phi = (k_\perp/k_\theta)\delta\phi$ and $\delta\Psi = (k_\perp/k_\theta)\delta\psi$ in asymptotic series in powers of $\beta^{1/2}$[5] we obtain, in zeroth order of the quasineutrality condition, $\delta\Phi^{(0)} = I_\Phi(\omega,\overline{\omega}_{Di,e},\omega_{*i,e})\delta\Psi^{(0)}$. Here, $I_\Phi \simeq 1$ for most of the Alfvenic spectrum (except frequencies near precession resonance $\overline{\omega}_{Di,e}$), consistently with the ideal MHD limit $\delta E_\parallel = 0$. Further expansion of the quasineutrality condition gives $\delta\Phi_s = S(\omega,\omega_{Bi},\overline{\omega}_{Di,e},\omega_{Ti})\xi\delta\Phi^{(0)}$, where $\xi \simeq k_\perp/k_\theta$ and $\delta\Phi_s \sim O(\beta^{1/2})$ is the $\sim\sin\theta$ modulation of the potential along magnetic field line, which makes the function $|S|$ a measure of how much the mode polarization deviates from pure Alfv\'enic due to the parallel a.c. electric field.

The generalized inertia is obtained from the vorticity equation expanded to $O(\beta)$[7]:

$$\Lambda^2/I_\Phi = \frac{\omega^2}{\omega_A^2}\left(1-\frac{\omega_{*pi}}{\omega}\right) + \Lambda^2_{cir} + \Lambda^2_{tra}\ ,$$

where Λ^2_{cir}[5] and Λ^2_{tra}[7] are the circulating and trapped particles contributions, respectively. Even though this expression of Λ is a mixture of deeply trapped and well circulating particle responses, it has been shown[7] that this reduced model recovers well the low and high frequency limits of the continuous spectrum, and further gives good insights into experimental results. The term I_ϕ acts as an additional inertia enhancement due to the opposite precessional motion of trapped ions and electrons around the torus. In Ref.[8], the equation $\Lambda = 0$ was solved for BAE/KBM/BAAE branches at the accumulation points of each of them, without the presence of EPs. The frequency of KBMs is found to be close to $\omega_{*pi} = (T_ic/e_iB)(\mathbf{k}\times\mathbf{b})\cdot\nabla p_i/p_i$, although this can change due to the coupling with the BAAE mode. ω_{*pi} affects the polarization $|S|$ and reduces the otherwise large damping rate of BAAEs 6,8. In our model, modes with Alfvenic polarization have $\delta\Phi^{(0)} = \delta\Psi^{(0)}$ and $|S| \sim \beta^{1/2}$, while modes with significant acoustic component, such as BAAEs are identified by $|S| \gg \beta^{1/2}$.

When RHS of GFLDR is taken into account the potential $\delta\bar{W}_f(s,\alpha)$[10] determines the MHD stability of the mode, while the energetic particle term $\delta\bar{W}_k$ the EP drive [9]. Due to the low frequency of the modes, here we focus on the resonant interaction with the thermal particle precessional motion, which for deeply trapped ions can be described by the EP term [1] in the small FLR/FOW limit:

$$\delta\bar{W}_{kt} = \frac{2\pi^2e^2}{mc^2|s|}qR_0B_0\int d\varepsilon\int d\mu\,(\overline{\omega}_d/k_\theta)^2\tau_b\,QF_0\frac{1}{\overline{\omega}_d-\omega}\,.$$

Here, τ_b is the thermal ion bounce period and $QF_0 = (\omega\partial_\varepsilon + (\mathbf{k}\times\mathbf{b})/\omega_c\cdot\nabla)F_0$.

In the case of BAAEs, solutions of the GFLDR show, consistently with the experiment, that the core plasma effects (ω_* and $\overline{\omega}_{Di}$ resonance) play a crucial role in the excitation of the mode, much more than the energetic particles. The low frequency Alfvenic mode, which we identify as KBM, is easier to excite and closely related to the ion diamagnetic frequency. Our work shows that GFLDR is a general and comprehensive tool illuminating the nature of the fluctuations, appropriate for understanding the effects of EPs and core plasma on the low frequency modes, as well as for explaining the experimental observations.

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Country or International Organization

Korea, Republic of

Affiliation

National Fusion Research Institute

Author: CHAVDAROVSKI, Ilija (National Fusion Research Institute)

Co-authors: ZONCA, Fulvio (Associazione EURATOM-ENEA sulla Fusione); CHEN, Liu (Zhejiang University)

Presenter: CHAVDAROVSKI, Ilija (National Fusion Research Institute)

Session Classification: P5 Posters 5

Track Classification: Magnetic Fusion Theory and Modelling