Sub-GAM Modes in Stellarators and Tokamaks

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Abstract. Equations describing eigenmodes with the frequencies of the order of the geodesic acoustic frequency and the electron/ion diamagnetic frequency in toroidal plasmas are derived and analyzed, a code BOAS solving them is developed. It is shown that there exist drift-sound eigenmodes and new drift-Alfvén eigenmodes. This is done by means of an analytical consideration and numerical modelling of particular discharges in the stellarator Wendelstein 7-AS. It is shown experimentally that the modes rotating in different directions can be destabilized simultaneously, which agrees with theory predictions.

1. Introduction

Recently, instabilities with frequencies below that of the Toroidicity-induced Alfvén Eigenmodes (TAE) attracted considerable attention in fusion research. These Low Frequency (LF) instabilities occur in all types of toroidal plasma systems. In particular, Reversed Shear Alfvén Eigenmodes (RSAE) or Alfvén Cascades (AC) were observed in JET and extensively studied theoretically [1, 2]; Non-conventional Global Alfvén Eigenmodes (NGAE) were predicted to exist in stellarators and seem to be observed in Wendelstein 7-AS (W7-AS) [3, 4]; Beta-induced Alfvén Acoustic Eigenmodes (BAAE) were observed in the NSTX spherical torus [5], the Sound Cascades (SC) were observed in ASDEX-Upgrade [6]. Despite efforts of many theorists, a number of features of experimentally observed LF instabilities remain a mystery. In particular, it is not clear why the BAAE modes, which are actually sound waves, are not strongly damped but easily destabilized in isothermic plasma; why a LF instability observed in DIII-D manifests itself even at any beam power [7]. Furthermore, there are different interpretations of Beta-induced Alfvén Eigenmodes (BAE) observed in DIII-D many years ago [8]. Both the BAAE in NSTX and the mentioned instabilities in DIII-D have the frequencies below the frequency of the Geodesic Acoustic Mode (GAM), ω_G [9]. The modes with the frequencies below/about ω_G, which we may refer to as sub-GAM modes, were observed also in W7-AS. The nature of some of them remains unclear. The purpose of this work is to contribute to understanding the physics of sub-GAM instabilities and to apply a new theory to modelling experiments on W7-AS [10].

Our basic idea is that plasma compressibility and finite diamagnetic frequencies of the electrons and ions, ω_{*e} and ω_{*i}, play an important role in LF instabilities. Taking them into account may immediately explain why sound perturbations are weakly damped even in isothermic plasmas: due to finite ω_* the frequency of sound perturbations does not go to zero when $k_\parallel \to 0$ ($k_\parallel$ is the longitudinal wave number), which implies that $\omega/k_\parallel \gg v_{\mathrm{th},i}$ (ω is the wave frequency, $v_{\mathrm{th},i}$ is the ion thermal velocity) when $k_\parallel$ is sufficiently small. Moreover, finite ω_* breaks the symmetry of the dispersion relation with respect to the sign of ω, which, in particular, may lead to the existence of new modes. It follows from the foregoing that the ideal MHD approximation may be insufficient for the description of LF modes. Note that this was realized long time ago; nevertheless, typically one usually uses ideal MHD to describe destabilized eigenmodes. On the other hand, studies beyond ideal MHD showed new interesting results: Kinetic Ballooning Modes (KBM) and Energetic Particle Modes (EPM) of drift type were predicted [11], and new features of LF instabilities were revealed due to taking into account plasma compressibility and the ion diamagnetic frequency on the same footing [12]. However, the mentioned results are relevant only to Alfvén perturbations; another important class of perturbation — sound perturbations — is not considered yet. Moreover, the mentioned Alfvén perturbations are studied in the framework of ballooning formalism, which describes EPM and gap modes localized at rational flux surfaces but cannot describe the modes with frequencies close to extrema of Alfvén continuum away from the rational surfaces [like Global Alfvén Eigenmodes (GAE), NGAE and RSAE] and requires additional efforts to calculate the radial structure of the modes. This motivated us to derive new equations describing both drift-Alfvén perturbations and drift-sound perturbations. A difficulty to be overcome in this way is that the equations for perturbations of the drift-sound type do not contain radial derivative terms and, thus, determine only continuum but not eigenmodes. We assume that the problem can be resolved due to the magnetic field inhomogeneity, which couples the drift-sound perturbations with the drift-Alfvénic perturbations.

2. Basic equations and the code BOAS

We proceed from the collisionless fluid equations derived in Refs. [13, 14], which take into account the anisotropy of the plasma pressure and the gyroviscous cancellation [15]. We assume that $v_{\mathrm{th},i} \ll \omega/k_\parallel \ll v_{\mathrm{th},e}$, where $v_{\mathrm{th},e}$ is the electron thermal velocity. In this case the longitudinal thermal flux dominates the electron energy balance; therefore, the electron temperature is flattened out along the field lines: $\mathbf{B}\cdot\nabla T_e = 0$ (with $\mathbf{B}$ the magnetic field strength and T_e the electron temperature), which implies that the electron temperature remains isotropic in the perturbed state. In addition to this equation, we use the equation of motion (without the inertia term) and the quasi-neutrality condition $n_e = n_i$ (where $n_{e/i}$ is the electron/ion density) to describe electrons. For the ion component, we neglect the longitudinal thermal fluxes due to the condition $\omega/k_\parallel \gg v_{\mathrm{th},i}$ (this implies that there is no mechanism to maintain the pressure isotropy and, thus, the perturbed ion pressure is strongly anisotropic). To eliminate fast magnetoacoustic waves from the consideration, we take into account that the Alfvén waves and the sound waves weakly disturb the total perpendicular pressure of the magnetic field and plasma. For low-β plasmas, the plasma pressure can be neglected, which leads to the condition $\tilde{B}_\parallel \approx 0$ (tilde labels perturbations). Finally, we take the equilibrium magnetic field, B_0, and perturbed quantities, $\tilde{X}$, in the forms:

$$B_0 = \bar{B}\left(1 + \frac{1}{2}\sum_{\mu\nu} \epsilon_B^{(\mu\nu)}(r) e^{i\mu\theta - i\nu N\phi}\right), \quad \tilde{X} = \sum_{m,n} \tilde{X}_{m,n}(r) e^{im\theta - in\phi - i\omega t}, \tag{1}$$

where r, θ, and ϕ are Boozer coordinates, $\epsilon_B^{(-\mu,-\nu)} = \epsilon_B^{(\mu\nu)}$, N is the number of the field periods. Then we obtain the following set of equations (details will be published elsewhere):

$$\omega^2 (\omega - \omega_{*e}) \zeta_{mn} - k_{mn}^2 c_{ei}^2 [\omega - \omega_{*i} + 3\tau(\omega - \omega_{*e})]\zeta_{mn} = -\frac{c}{\bar{B}} c_{ei}^2 [\omega(1+2\tau) + \omega_{*i}] \times (\omega - \omega_{*i}) \frac{k_{m,n}^2}{r} \left[\mu \epsilon_B^{(\mu\nu)} \frac{d\Phi_{m+\mu,n+\nu N}}{dr} + (m+\mu) \frac{d\epsilon_B^{(\mu\nu)}}{dr} \Phi_{m+\mu,n+\nu N} \right], \quad (2)$$

$$\frac{1}{r}\frac{d}{dr} r \left[\frac{\omega^2 - \omega_G^2}{v_A^2} \left(1 - \frac{\omega_{*i}}{\omega}\right) - k_{m+\mu,n+\nu N}^2 \right] \frac{d\Phi_{m+\mu,n+\nu N}}{dr} - \left\{ \frac{(m+\mu)^2}{r^2} \left[\frac{\omega^2 - \omega_G^2}{v_A^2} \left(1 - \frac{\omega_{*i}}{\omega}\right) - k_{m+\mu,n+\nu N}^2 \right] + \frac{k_{m+\mu,n+\nu N}}{r} \left[(r k'_{m+\mu,n+\nu N})' - \frac{m+\mu}{R} (3\iota' + r\iota'')\nu_\iota \right] \right\} \Phi_{m+\mu,n+\nu N} = \frac{\bar{B}}{cr\omega\delta_0} \left[\frac{c_{ei}^2}{v_A^2} (1+2\tau) \frac{d\epsilon_B^{(\mu\nu)}}{dr} (m+\mu)\zeta_{mn} - \frac{d}{dr} \frac{c_{ei}^2}{v_A^2} (1+2\tau) \mu \epsilon_B^{(\mu\nu)} \zeta_{mn} \right], \quad (3)$$

where Φ is the perturbed scalar potential of the electromagnetic field, $\zeta_{mn} \equiv i\omega\nabla_\parallel \tilde{v}_{\parallel mn}$, with $\tilde{v}_\parallel$ the longitudinal perturbed velocity of the ion component, $\tau = T_i/T_e$, $T_{e/i}$ is the electron/ion temperature, $k_{mn} = (m\iota - n)/R$ is the longitudinal wave number, R is the major radius of the torus, ι is the rotational transform, $c_{ei}^2 = T_e/M_i$, M_i the ion mass, $\omega_{*i} = mcp_i'/(e_i B n_i r)$ and $\omega_{*e} = mcT_e n_e'/(e_e B n_e r)$, with p_i the ion pressure, prime denotes the radial derivative, ν_ι is the fraction of the rotational transform produced by the plasma current ($\nu_\iota = 1$ in tokamaks, $\nu_\iota = 0$ in currentless stellarators), $\delta_0 \gtrsim 1$ characterizes the plasma shape [4],

$$\omega_G = \frac{c_{ei}}{R}\frac{\epsilon_t}{\epsilon}\sqrt{\frac{2}{\delta_0}\left(1 + \frac{7}{4}\tau\right)}. \quad (4)$$

In these equations, Φ describes Alfvénic perturbations, whereas ζ describes perturbations of the sound type. The magnitudes Φ and ζ are coupled due to finite $\epsilon_B^{(\mu\nu)}$. For simplicity, the coupling terms were derived in assumptions of homogeneous plasma temperature and high mode numbers; in addition, we took $\delta_0(r) = \text{const}$ and $\nu_\iota(r) = \text{const}$. Equation (4) is written with taking into account that harmonics with high μ, ν weakly contribute to ω_G (see Ref. [4]); in addition, harmonics of B_0 with $\mu > 1$ are neglected (therefore, ω_G is somewhat underestimated).

In order to solve coupled drift-sound and drift-Alfvén equations, a numerical code BOAS (Branches Of Alfvén and Sound modes) was developed. The code calculates both the continuum and discrete modes and can allow for FLR effects.

3. Drift-sound and drift-Alfvén eigenmodes

Let us analyze these equations. First of all, we consider the continuum, assuming that the coupling terms weakly disturb it. The continuum branches depend on the ratio of ω_G/ω_{*i}. A sketch of them for $\omega_G > \omega_{*i}$ is shown in Fig. 1. Note that we took $\omega > 0$ for the modes rotating in the ion diamagnetic direction and $\omega < 0$ for the modes rotating in the electron direction, in which case $m < 0$ and $n < 0$. We observe that there are

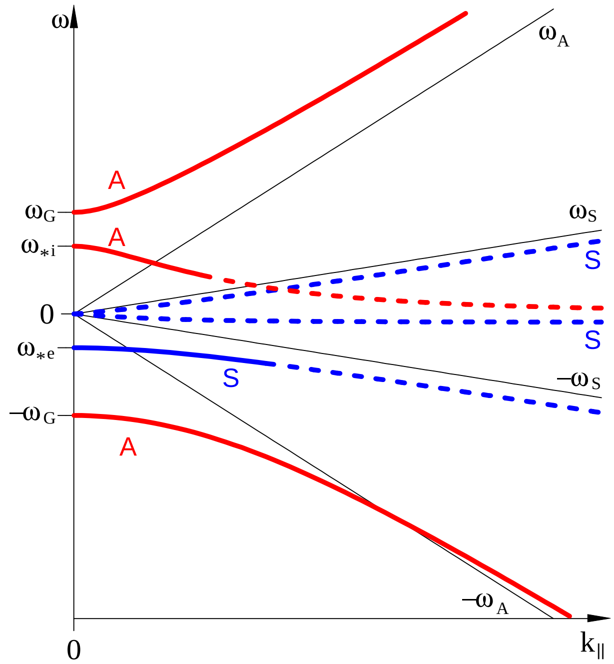

FIG. 1. Sketch of drift-Alfvén (labeled "A") and drift-sound (labeled "S") continuum branches for $\omega_G > \omega_{*i} > |\omega_{*e}|$. Notations: $\omega_A = k_\parallel v_A$, $\omega_s = k_\parallel c_s$, with c_s the sound velocity. When $T_e = T_i$, only the parts of branches shown by bold lines are of interest because dotted lines lie in the region where $\omega \sim k_\parallel v_{\mathrm{th},i}$, i.e., where the modes are strongly damped.

Alfvén branches with both $\omega > 0$ and $\omega < 0$, but when $\omega < \omega_{*i}$, the Alfvén frequencies are positive. The sound continuum branch near which weakly damped modes are possible is negative. Similar conclusions can be drawn when $\omega_G < \omega_{*i}$ and $\omega_G < |\omega_{*e}|$ despite different behaviour of the continuum branches.

In order to see whether drift-sound modes exist in the framework of our model, we consider the simplest case of $\mu = \nu = 0$. Then the drift-Alfvén and drift-sound continua are decoupled; nevertheless, the equations determine the structure of drift-sound modes due to finite $\epsilon_B^{(00)}$. We write Eqs. (2), (3) for $\nu_\iota = 0$ as follows:

$$S\zeta_{mn} = p_1 \Phi'_{m+\mu,n+\nu N} + p_2 \Phi_{m+\mu,n+\nu N}, \tag{5}$$

$$\frac{d}{dr} A \frac{d\Phi_{m+\mu,n+\nu N}}{dr} - \left[\frac{(m+\mu)^2}{r^2} A + k_{m+\mu,n+\nu N} (r k'_{m+\mu,n+\nu N})' \right] \Phi_{m+\mu,n+\nu N} = (q_1 \zeta_{mn})' + q_2 \zeta_{mn}, \tag{6}$$

where the coefficients can be easily determined by comparing Eqs. (5), (6) with Eqs. (2), (3). We consider Eqs. (5), (6) in the vicinity of an extremum of the drift-sound continuum. Following an approach used in Ref. [16] to study well-localized Alfvén eigenmodes, we obtain the following Schrödinger-type equation for $\mu = \nu = 0$:

$$\frac{d^2\Psi}{dx^2} + [E - U(x)]\Psi = 0, \tag{7}$$

where $\Psi = \sqrt{A}\Phi_{mn}$, $x = (r - r_0)/\Delta$, r_0 the radius where the continuum defined by $S(r_0, \omega) = 0$ has an extremum, $\Delta^2 = 2S/S''|_{r_0}$, the energy (E) and the potential ($U(x)$)

are defined by

$$E = -\left[\frac{m^2}{r^2} + \frac{k_{mn}(rk'_{mn})'}{A} + \frac{A''}{2A} - \left(\frac{A'}{2A}\right)^2\right]\Delta^2, \tag{8}$$

$$U(x) = \frac{2p_2q_2}{AS''}\frac{1}{1+x^2}, \tag{9}$$

where all the magnitudes are taken at the point r_0. One can see that $A < 0$ (at least, when $\omega^2 < \omega_G^2$ or $\omega^2 < k_\parallel^2 v_A^2$), $p_2q_2 > 0$ and $S_\omega \equiv \partial S/\partial\omega > 0$ for $\omega < 0$; $S''S_\omega > 0$ at the maximum of the continuum and $S''S_\omega < 0$ at the minimum. Therefore, there is a potential well at the maximum, and a hill at the minimum. The energy is typically negative (the first term dominates in Eq. (8), and $\Delta^2 > 0$ for discrete modes). We conclude from here that discrete drift-sound eigenmodes exist when the continuum has a maximum (for $\omega < 0$).

Drift-Alfvén eigenmodes can also be described by a Schrödinger-like equation. Neglecting the mode coupling, we have:

$$\frac{d^2\Psi}{dr^2} + [E_1 - U_1(r)]\Psi = 0, \tag{10}$$

where $E_1 = 0$ and $U_1(r) = -E/\Delta^2$. A condition of the existence of discrete eigenmodes (not necessary well localized) is $U_1(r) < 0$ in some region, which provides the presence of two "turning points". Discrete eigenmodes exist even when $U_1(r) < 0$ in the whole plasma cross section provided that $\Psi(a) = 0$, with a the plasma radius [4].

4. Kinetic eigenmodes

Considering the case of $\mu \neq 0$, we take into account effects of the finite ion Larmor radius (FLR) by adding a fourth-derivative term, $\alpha r d^4\Phi_{m+\mu,n+\nu N}/dr^4$, to the left-hand side of Eq. (6), where α is proportional to square of the ion Larmor radius (see Ref. [17] for the case of $\omega > \omega_*$). Eliminating ζ from Eqs. (5) and (6), we obtain the following equation for drift-Alfvén and drift-sound eigenmodes:

$$\frac{d}{dr}F\frac{d\Phi_{m+\mu,n+\nu N}}{dr} - \left[\frac{(m+\mu)^2}{r^2}F - g\right]\Phi_{m+\mu,n+\nu N} + \alpha r\frac{d^4\Phi_{m+\mu,n+\nu N}}{dr^4} = 0, \tag{11}$$

where $F = A - p_1q_1/S$, $g = -k_{m+\mu,n+\nu N}(rk'_{m+\mu,n+\nu N})' - (q_1p_2/S)'$. Note that in the ideal limit case ($\alpha = 0$) Eq. (11) possesses a continuous spectrum described by the equation $F = 0$ ($AS = p_1q_1$). We approximate $F(r)$ as $F = F_\omega(\omega - \omega_0)(1 + x^2)$, where $x = (r - r_0)/\Delta$, $\Delta^2 = 2F_\omega(\omega - \omega_0)/F''$, F_ω and F'' are taken at a point (r_0, ω_0) where the continuum has an extremum. Assuming the rest of coefficients to be constant, we perform the Fourier transformation: $\Phi_{m+\mu,n+\nu N}(x) = \int dp \exp(ipx)\hat{\Phi}(p)$. The obtained equation can be reduced to the Schrödinger equation (7), in which $\Psi = (1+\bar{p}^2)^{1/2}\hat{\Phi}$, $\bar{p} = p/\mathcal{M}^{1/2}$ plays the role of x, $E = -\mathcal{M}$, $\mathcal{M} = \Delta^2(m+\mu)^2/r_0^2$,

$$U(\bar{p}) = \frac{1}{(1+\bar{p}^2)^2} - \frac{\bar{g}}{1+\bar{p}^2} - \frac{2(m+\mu)^4\alpha}{r_0^3F''}\frac{\bar{p}^4}{1+\bar{p}^2}, \tag{12}$$

where $\bar{g} = 2g/F''$. In the ideal case ($\alpha = 0$), Eq. (7) with U given by Eq. (12) possesses a discrete spectrum when $\bar{g} > 1/4$ [18]. The effect of the FLR term is determined by the sign of F''. When $F'' < 0$ and $\alpha > 0$, FLR produces new modes in the continuum of the ideal equation (even when $\bar{g} < 1/4$ and ideal modes are absent); we refer to them as Kinetic Drift-Alfvén Eigenmodes (KDAE) and Kinetic Drift-Sound Eigenmodes (KDSE). In the contrary case, $F'' > 0$, FLR results in radiative damping of ideal modes. Typically, KDSEs exist below the maximum of the continuum (because $F_\omega < 0$). In the case of $\omega_G > \omega_{*i}$, KDAEs exist below the maximum when either $0 < \omega < \omega_{*i}$ or $\omega < 0$ and $|\omega| > \omega_G$; they exist above the minimum for $\omega > \omega_G$ (like kinetic GAEs [19]).

5. Low-frequency instabilities in W7-AS

An analysis of several different W7-AS discharges (#39029, #43348, #54022 and others) confirmed the supposition based on Fig. 1 that the modes with lowest frequencies may rotate in the direction of the electron diamagnetic velocity, in contrast to the modes with higher frequencies. Figure 2 demonstrates this for the modes the discharge #39029. The lowest frequency in most of the mentioned discharges were about 9 kHz, but 18 kHz in the discharge #43348. On the other hand, the 16 kHz mode in the discharge #40173 rotated in the ion diamagnetic direction. Therefore, one can suppose that drift-Alfvén modes were destabilized in the latter discharge, whereas drift-sound modes were destabilized in the former ones. A numerical modelling of LF instabilities in the W7-AS discharges #39029

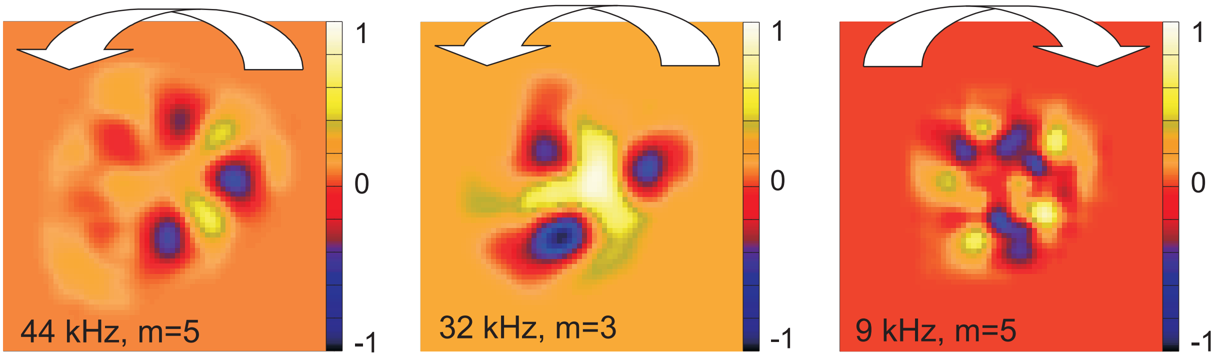

FIG. 2. Tomographical reconstruction of soft X-ray data in the W7-AS discharge #39029 (time range 0.500 - 0.501 s). The high-frequency mode rotates in the ion diamagnetic direction, whereas the low-frequency mode rotates in the electron diamagnetic direction.

and #40173 was carried out. Earlier these discharges were analyzed in Refs. [4, 20], where some of the observed modes were identified as GAE and NGAE modes. However, theory of the mentioned works failed to explain the existence of the modes with the lowest frequencies (9 kHz in the discharge #39029 and 16 kHz in the discharge #40173). Now we can suggest an explanation: The code BOAS finds new modes. One of them, in the discharge #39029, is a drift-sound mode ($m = -5$, $n = -2$), see Fig. 3; the existence condition of KDSE modes is satisfied in this case. Thus, the observed mode may be either "ideal" or kinetic mode. Another one, in the discharge #40173, is a drift-Alfvén mode, which appears near the lowest branch with $\omega > 0$ in Fig. 1. The found modes satisfy the condition $v_{\mathrm{th},i} \ll \omega/k_\parallel \ll v_{\mathrm{th},e}$. They can be destabilized by injected beam ions through the resonance $\omega = (k_{m+\mu,n+\nu N} \pm \iota/R)v_\parallel^{\mathrm{res}}$ due to the velocity anisotropy. A solution of this

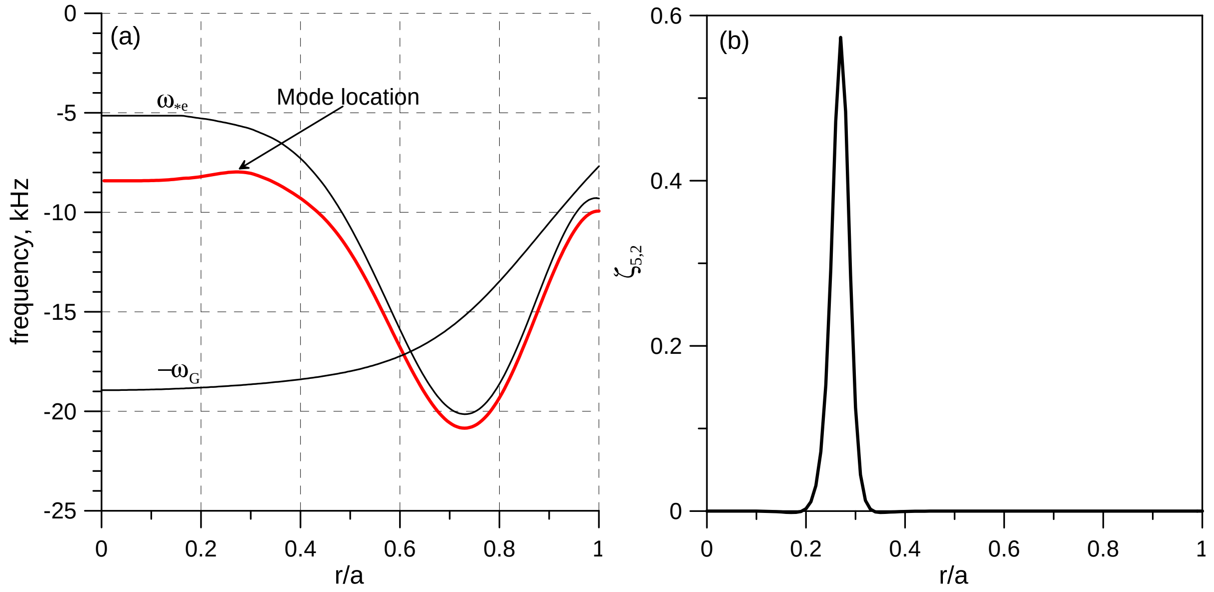

FIG. 3. Modelling of the 9-kHz instability in the W7-AS discharge #39029: (a) drift-sound continuum branch (in red), ω_G, and ω_{*e}; (b) the $\zeta_{5,2}(r)$ component of the KDSE-mode. The $\Phi_{6,2}(r)$ component of KDSE (not shown here) is considerably wider but has much smaller amplitude.

equation is $v_\parallel^{\rm res}/v_0 = 0.63$ (v_0 is the velocity of injected ions) in the discharge #39029, which means that the drive can exceed the damping when $0.63 < \chi < 0.77$, where χ the pitch angle of fast ions (this condition is obtained for the distribution function $f_b \propto \delta(\chi - \chi_0)/v^3$ by using the result of Ref. [21]). In addition, spatial inhomogeneity of the electrons may contribute to the destabilization of the modes with $\omega < 0$.

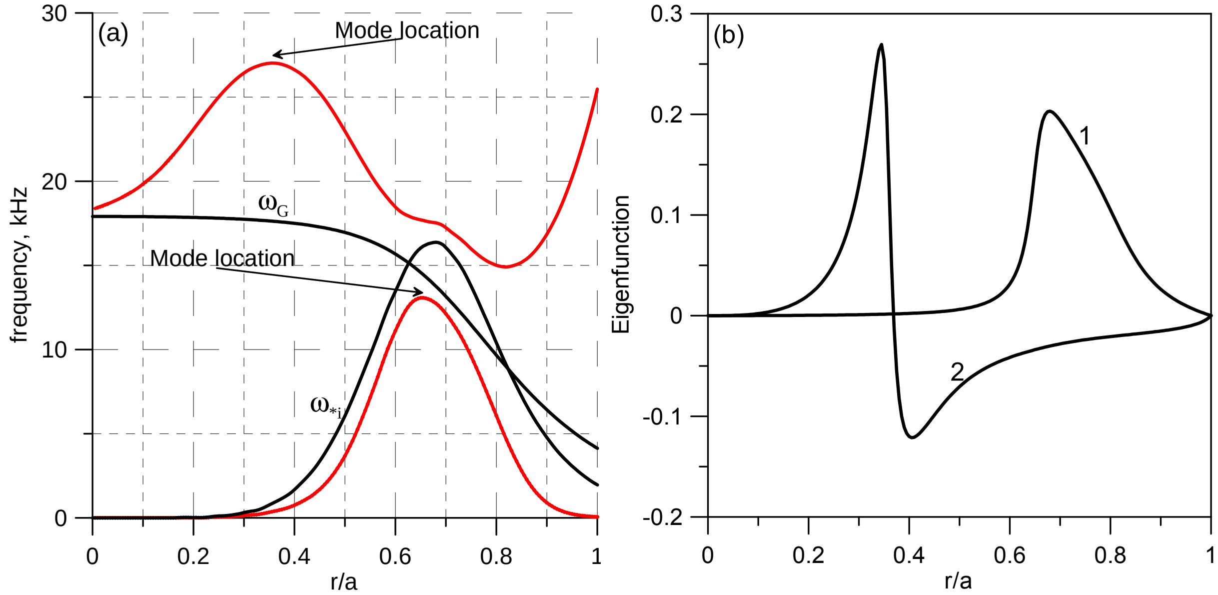

FIG. 4. Modelling of instabilities in the W7-AS discharge #40173: (a) drift-Alfvén continuum (in red), ω_G, and ω_{*i}; (b) eigenmodes. The mode with $\omega < \omega_{*i}$, curve 1, is absent in the ideal MHD. The mode with higher frequency, curve 2, is NGAE [4]. The latter has a node, in agreement with the experiment.

6. Summary

Equations describing eigenmodes of both drift-Alfvén type and drift-sound type are derived. A code BOAS solving these equations is developed. It takes into account factors neglected in ideal MHD codes and can be used for analysis of MHD perturbations in any type of toroidal fusion devices. Conditions of existence of LF modes are obtained. Modelling of W7-AS discharges where instabilities in a wide frequency range were observed was carried out. The instabilities with the lowest frequencies were identified as a destabilized drift-sound mode and a drift-Alfvén mode. Note that these modes are absent in ideal MHD and cannot be described by previous theories based on the ballooning formalism (they are localized away from the rational flux surface). Thus, the existence of drift-sound modes in toroidal plasmas is shown for the first time and new drift-Alfvén modes (with $\omega \lesssim \omega_{*i}$) are predicted. It is shown experimentally that the modes rotating in different directions can be destabilized simultaneously, which agrees with theory predictions.

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