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Exciting and propagating characteristics of two coexisting kinetic geodesic acoustic modes in the edge of plasma

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Abstract

Coexisting dual kinetic geodesic acoustic modes (KGAMs) with similar characteristics have been observed with Langmuir probe arrays in the edge plasma of HL-2A tokamak with low density Ohmic discharge. The dual KGAMs are named a low-frequency GAM (LFGAM) and a high-frequency GAM (HFGAM), respectively. By changing the line averaged density from $1.0 \times 10^{19}$ m$^{-3}$ to $0.7 \times 10^{19}$ m$^{-3}$, the study of $n_e$ and $T_e$ profiles indicate that collision damping rate plays a crucial role on exciting of dual KGAMs, especially for the higher frequency branch (HFGAM). With the application of modulating techniques, we provide direct proof that nonlinear interactions between GAMs and ambient turbulence (AT) show great difference at different radial positions. At the exciting position of GAM, the amplitude modulation of AT is dominant, indicating that GAM is generated in the energy-conserving triad interaction. After the exciting of GAMs, they will propagate both inward and outward. During the propagation, the phase modulation of AT is dominant, GAMs can rarely gain energy from AT, yet they can give back-reactions on AT through shearing effect.

Keywords: zonal flow, kinetic GAM, ambient turbulence

(Some figures may appear in colour only in the online journal)
sheared flow could be developed from drift waves as a second instability and that the formation of the sheared flow structure in the mesoscale, i.e. zonal flows, could give back-reactions on the micro-scale drift wave turbulence. This kind of mutual interaction between zonal flow and turbulence is emphasized as the process of determining turbulence saturation and transport levels.

The schematic view of the system of zonal flows and drift waves provided above is mainly established on the understanding of continuum GAM, which was first derived via fluid theory and linear dependence of GAM frequency on the ion acoustic velocity \( C_i \). However the existence of GAM eigen-modes were also reported, especially in the edge plasma. In JFT-2M [5], it was found that the GAM frequencies remained constant along the radial direction at several centimeters just inside the last closed flux surface(LCFS) and similar results have also been observed in HL-2A [6] and HT-7 [7]. Besides, phenomena of multi-GAMs or splitting GAMs at edge plasma have also been reported on T-10 [8], ASDEX-U [9] and HT-7 tokamak [10]. Our previous work on HT-7 summarized those phenomena and provided a set of proofs that the GAM with eigen-frequency observed in the edge plasma may be the kinetic GAM (KGAM) [11–15], which is converted from a continuum GAM. After its excitation, the KGAM will propagate both inward and outward with its frequency remaining the same during the process. Although many theoretical and experimental works have been done to study the KGAM and have achieved fruitful conclusions, especially the mode structure characteristics of KGAM [10]. Yet, the mechanism of exciting and propagating characteristics of KGAM and its nonlinear interactions with drift-turbulence of these two processes still remain unknown. Another important issue of KGAM is the exciting mechanism of multi-GAMs.

In this work, two coexisting GAMs are observed through Langmuir probe arrays in the edge plasma with a low collisionality approached by low average density discharge \( (n_e < 1.0 \times 10^{19} \text{ m}^{-3}) \) on the HL-2A tokamak. These two coexisting GAMs of different frequencies are named high frequency GAM (HFGAM) and low frequency GAM (LFGAM) for convenient. The radial distributions of central frequency and radial wavenumber of these GAMs all suggest that they are kinetic GAMs, which are similar to the observations on HT-7. The probe arrays are just fixed at the exciting position of LFGAM, where is the propagating point for HFGAM. By comparing the difference of nonlinear interactions of LFGAM and HFGAM with ambient turbulence (AT), we find out that GAM mainly gain energy from AT at the exciting position by amplitude modulation instability. During the propagation, GAM mainly suppress the AT by phase modulation instability, corresponding shearing effect of GAM here.

The experiments are carried out on HL-2A \((R = 1.65 \text{ m}, a = 0.4 \text{ m})\) with divertor configuration under the following discharge parameters: magnetic field \( B_t = 1.4 \text{ T} \), plasma current \( I_p = 165 \text{ kA} \), safety factor at the \( \rho = r/a = 0.95 \), \( q_{95} = 3.4 \), and line-averaged density of the mid-plane \( n_e = 0.7 \sim 1.0 \times 10^{19} \text{ m}^{-3} \). The discharge gas is deuterium. During the experiments, line-averaged density is performed at 0.7 \( \times 10^{19} \), 0.8 \( \times 10^{19} \) and 1.0 \( \times 10^{19} \text{ m}^{-3} \) respectively, while all other parameters remain the same. Measurements are carried out by two radially reciprocating probe systems marked A and B. Both systems are performed on the midplane of the tokamak. Probe system A is a standard four-tip probe, which can reciprocate and is used for measuring the electron temperature as well as the density and floating potential, including the time-averaged profiles and fluctuations. Probe system B has two sets of radial ‘rake’ probes with poloidal separation of 11 cm. All rake probes are composed of four graphite tips equally separated by 2.5 mm, which are all used for measurements of the floating potential and their fluctuations. The deepest insertion position of the probe tip is \( \rho = 0.95 \text{ cm} \). This arrangement allows simultaneously measurement of the floating potential fluctuations in three dimensions with large poloidal and toroidal separations and thus determination of the three-dimensional structure of zonal flows with less disturbance of ambient turbulence. Such an arrangement has proven to be effective for zonal flows research [16]. The effect of neglecting electron temperature fluctuations on probe fluctuation measurements, in particular the relative fluctuation level of plasma potential, had been studied before [17, 18]. The results show that neglecting temperature fluctuation does not fundamentally change estimation results. Therefore, floating potential \( V_f \) is applied to study the potential characteristics of turbulence. The sampling frequency is 1 MHz with a Nyquist frequency of \( f_N = 500 \text{ kHz} \).

With the reciprocating probes moving from \( r = 45 \text{ cm} \) to \( r = 37 \text{ cm} \), \( T_e \) increased from \( 9 \text{ eV} \) to \( \sim 90 \text{ eV} \) and \( n_e \) increased from \( 2 \times 10^{17} \text{ m}^{-3} \) to \( 3.4 \times 10^{18} \text{ m}^{-3} \) . \( T_e \) and \( n_e \) remained almost the same from 700 ms to 1000 ms, as illustrated in figures 1(c) and (d). The temporal evolution of spectra of the local floating potential \( V_f \) is shown in figure 1(e). It can be seen that two coherent modes can be observed with peak frequencies at \( f = 10.5 \text{ kHz} \) and \( f = 17.5 \text{ kHz} \), respectively. The two coherent modes are coexisting with each other and can only be observed inside the separatrix. It needs to be noticed that no coherent modes with similar peak frequencies can be found from the Mirnov signals at the edge. Those results indicate that both of the coherent modes are electrostatic fluctuations. Probe signals jump unnormally at around 1080 ms.

To identify these two electrostatic modes, their mode structures have been studied. Figures 2(a) and (b) provide the coherence and cross-phase spectra of two potential fluctuations measured by probes located at the same flux surface with the toroidal separations of 130 cm. It can be seen that both features have high coherence and phase-shifts of nearly zero. The poloidal and toroidal mode numbers are evaluated to be \( m = -0.1 \pm 0.2 \) and \( n = 0.5 \pm 0.1 \) for low frequency feature and \( m = 0.02 \pm 0.2 \) and \( n = -0.2 \pm 0.1 \) for the high frequency feature respectively. Both of the two features can be regarded as poloidally and toroidally symmetric modes of \( m = 0 \) and \( n = 0 \). Furthermore, according to the measured electron temperature, the GAM frequency calculated from \( f_{\text{GAM}}^{\text{th}} = \sqrt{\left( T_e + 7/4 \cdot T_i \right) / m_e / q / 2 \pi R_0} \) is \( 11 \text{ kHz} \) with the assumption of \( T_i = T_e \) as illustrated the blue line in figure 1(e), which seems to access the mode peaking at 10.5 kHz. Thus, the 10.5 kHz coherent mode is the GAM existed just at the probe
position, while the 17.5 kHz coherent mode may be another GAM generated inside then propagated outward. To distinguish the coexisting GAMs, the two modes at 10.5 kHz and 17.5 kHz would be called a low-frequency GAM (LFGAM) and a high-frequency GAM (HFGAM), respectively, in the following.

Figure 2(c) shows a contour plot of wavenumber-frequency spectrum $S(k_r, f)$ below 30 kHz estimated from two $\tilde{V}_f$s separated by $d_\phi = 130$ cm and $d_r = 5$ mm. 

Figure 2. (a) Coherency and (b) cross-phase spectra between two $\tilde{V}_f$s with poloidal (black dash) and toroidal (red solid) separations of 11 cm and 130 cm, respectively. Wavenumber-frequency spectrum $S(k_r, f)$ below 30 kHz estimated from two $\tilde{V}_f$s separated by $d_\phi = 130$ cm and $d_r = 5$ mm.
and $\sigma_k = 1.8 \text{ cm}^{-1}$, while for the HFGAM, $k_r = 0.4 \text{ cm}^{-1}$ and $\sigma_k = 1.0 \text{ cm}^{-1}$. Those results imply that LFGAM packets propagate in radially inward direction, while HFGAM packets propagate in radially outward direction. The characteristics, especially the property propagation of LFGAM and HFGAM will be given.

Figure 3 shows the auto-power spectra of $V_f$, the summed square auto-bicoherence $\Sigma \psi^2$ for $f = f_{LFGAM}$ and $f = f_{HFGAM}$, respectively, the central frequencies and the radial wavenumbers of LFGAM and HFGAM at different radial positions inside the separatrix. Figure 3(a) illustrates the radial distributions of amplitude and central frequency of the LFGAM and HFGAM. It can be seen that the amplitude of LFGAM and HFGAM keep growing in the radially inward direction, while the amplitude of ambient turbulence have maximum value at $r = 37.25 \text{ cm}$. From figure 3(c), it could be found that the central frequencies of both LFGAM and HFGAM remained almost constant in the range of measurement. To study the relationship between the LFGAM, the HFGAM and the continuum GAM, the theoretic GAM frequencies $f_{GAM}^{th}$ are also plotted, as illustrated the blue diamond points in figure 3(c). It seems that the frequency of LFGAM is consistent with the continuum GAM frequencies at $r = 37.3 \text{ cm}$, which happen to be the positions where $k_r$ is close to zero. Similar stories happen on the HFGAM, which may generate in the deeper position, contrasting to LFGAM, then propagates outward with $k_r > 0$ and its amplitude decaying in propagation. The whole phenomenon is consistent with the mode conversion process from a continuum GAM to a kinetic GAM (KGAM) theory and simulations.

The eigenmode-type properties of KGAMs have already been reported on JFT-2M [5], ASDEX-U [9], HL-2A [6], DIII-D [19] and HT-7 [7, 10], as well as the simulations [14]. Unlike the results observed on HT-7 [10], which reported that the maximum amplitude of LFGAM was close to the generation position, figure 3(a) shows that the maximum amplitude of LFGAM is about 3 mm deeper than the generation position.

Bispectral analysis is used to investigate the nonlinear interaction between the GAMs and ambient turbulence (AT), which is a powerful fluctuating analysis technique for detecting the strength of nonlinear three-wave interactions among the fluctuating quantities. A commonly used quantity is the

\[ \Sigma \psi^2(f_{LFGAM}) \]

\[ \Sigma \psi^2(f_{HFGAM})/2 \]

Figure 3. (a) Auto-power spectra of the floating potentials at four radial positions inside the LCFS; radial distributions of (b) summed square auto-bicoherence $\Sigma \psi^2(f)$ for $f = f_{LFGAM}$ and $f = f_{HFGAM}$; (c) the central frequencies and (d) the radial wavenumbers for LFGAM and HFGAM, and the profile of continuum GAM frequencies $f_{GAM}^{th}(r)$ is also plotted for comparison.
summed squared bicoherence $\Sigma \hat{b}^2(f)$, which is defined as a sum of $\hat{b}^2(f_1, f_2)$ for all $f_1$ and $f_2$ satisfying $f = f_1 + f_2$ and normalized by $N(f)$, the number of Fourier component for each $f$ in the summation. i.e. $\Sigma \hat{b}^2(f) = \Sigma_{f_1, f_2} \hat{b}^2(f_1, f_2)N(f)$, providing a degree of all the nonlinear interactions involving the frequency component $f$. Figure 3(b) shows the radial distributions of $\Sigma \hat{b}^2(f)$ for $f = f_{LFGAM}$ and $f = f_{HFGAM}$, respectively. The results indicate that the strength of nonlinear interactions with HFGAM keep growing in the radially inward direction, while the strength of LFGAM have a maximum value at $r = 37.25$ cm, which is close to the generation position of LFGAM, implying that LFGAM gets strongest interactions with other fluctuating quantities, mainly AT here, when being excited.

According to the theory of zonal flow generation based on parametric or modulational instability, the generation of zonal flow is accompanied by the envelope modulation of ambient turbulence. The envelope analysis approach used in various experiments [20, 21] is utilized to identify the interactions between the GAM and AT. Figures 4(a) and (b) show the coherence and cross-phase spectra between the GAM oscillation $V_{GAM}$ and the envelope of AT with frequency $f$. The direct and envelope modulation of AT by the LFGAM is shown in the coherence spectra with coherence of $\gamma_{LFGAM} \sim 0.25$ and $\gamma_{HFGAM} \sim 0.35$, respectively; both values are much larger than the statistic noise level. This result indicates that the AT can be modulated by both the LFGAM and HFGAM. Moreover, the cross phases around the LFGAM and HFGAM frequencies are estimated to be $\sim \pi$ (or $-\pi$) and $\sim -\pi/2$, respectively, implying different kinds of nonlinear interaction between LFGAM with AT and HFGAM with AT.

It has been suggested that those envelope modulations may result from the Doppler shift of the GAM velocity oscillation, or the direct regulation effect of the GAM on the AT during the GAM generation. The meaning of the phase shift between GAM and the envelope of AT has been investigated in our previous work [20]. In this investigation, we have constructed a model signal as:

$$X(t) = [1 + \alpha \cos(2\pi f_{GAM} t)] \times \sum_{n=\infty}^{x=\infty} Y(t) e^{i(2\pi f + \beta \sin 2\pi f_{GAM} t)} \Delta f$$

here $Y(t) = \sum_{n=\infty}^{x=\infty} Y(f) e^{i2\pi f t}$ is taken from experimental data without GAM. Because the GAM is a symmetric $E \times B$ velocity oscillation, it will induce a time-dependent Doppler frequency modulation to turbulence, i.e. $\omega_d(t) = k_B E_r,GAM/B_0$ and $\phi(f) = \int \omega_d dt = (k_B E_r,GAM/B_0 \omega_{GAM}) \sin(\omega_{GAM} t)$ with the phase modulation index $\beta = k_B E_r,GAM(B_0/\omega_{GAM})$. The direct regulation effect during the GAM generation can cause directly the amplitude modulation of turbulence, i.e. $1 + \alpha \cos(\omega_{GAM} t)$ with amplitude modulation index $\alpha$. Equation (1) is used to simulate the pure amplitude modulation ($\alpha = 0$ and $\beta = 0$) and phase modulation ($\alpha = 0$ and $\beta \neq 0$), as well as complex modulation ($\alpha = 0$ and $\beta = 0$) signal, respectively.

The simulation results reveal that for the pure phase-modulation signal $X_{PM}(t)$, the cross phase between the GAM and the envelope is close to $\pi/2$ radian, while for the pure amplitude modulation signal, the cross phase is close to zero or $\pi$ radian for the positive or negative index $\alpha$, respectively. In figure 4, the cross phase between LFGAM and the envelope of AT is $\sim \pi$ radian, suggesting that the observed envelope modulation of them is dominantly induced by the amplitude modulation effect of the GAM during the GAM generation. The envelope modulation of AT by the LFGAM is accompanied with the GAM generation in energy-conserving triad interactions with AT, which may cause a transfer of AT energy to GAM. The probe arrays are fixed just at the generation position of LFGAM, where is the propagation position for HFGAM. Thus the cross phase between HFGAM and the envelope of AT is $\sim -\pi/2$ radian, suggesting that the envelope modulation of them is dominantly induced by the phase modulation through the shearing effect of the GAM during the propagation.

The discharging conditions of dual GAMs on HL-2A have also been studied. Figures 5(a) and (b) illustrate the radial profiles of $n_e$ and $T_e$, respectively, which are measured by a reciprocating probe array under different line-averaged density. The density is performed at $n_{eh} = 0.7 \times 10^{19}$ m$^{-3}$, $n_{eh} = 0.8 \times 10^{19}$ m$^{-3}$ and $n_{eh} = 1.0 \times 10^{19}$ m$^{-3}$ shot by shot. Here, the ‘$n_{eh}$’ means the line-averaged density, which is measured by the HCN interferometer. This symbol is used to distinguish the electron density ‘$n_e$’ measured by the probes in the edge. With the $n_{eh}$ changed from $0.7 \times 10^{19}$ m$^{-3}$ to $1.0 \times 10^{19}$ m$^{-3}$, $n_e$ at the edge becomes higher while $T_e$ becomes lower, which means a decrease in the collision damping rate. Figure 5(c) shows the auto-power spectra of $V_S$ under those discharging density, which is normalized by the peak value of LFGAM power. It can be seen that the normalized power of HFGAM decreases when the discharging density increased from $0.7 \times 10^{19}$ m$^{-3}$ to $0.8 \times 10^{19}$ m$^{-3}$, and it almost disappear when $n_{eh}$ is increased to $1.0 \times 10^{19}$ m$^{-3}$. With low collision damping rate, the HFGAM can propagate longer in the radial direction, thus can be detected by the
probe arrays outside. Those results indicate that the decrease of the collision damping rate would benefit the generation and propagation of GAMs.

In conclusion, the generation and propagation characteristics of dual GAMs at the edge of HL-2A tokamak with low-averaged discharging density \( n_{eh} \) are studied through Langmuir probe arrays. The mode structure and radial propagation of the coexisting dual GAMs have been studied in detail. The toroidal and poloidal mode numbers of both LFGAM and HFGAM have been proven to be \( n = m = 0 \). Within the measurement range of the probe arrays inside the separatrix, it can be found that the central frequencies of the LFGAM and the HFGAM remain almost unchanged. The theoretically predicted GAM frequency and LFGAM frequency got a crosspoint at \( r = 37.25 \) cm where the radial wavenumber of LFGAM happen to be 0 (\( k_r LFGAM \sim 0 \)). Those characteristics of the dual GAMs are consistent with the predictions of the kinetic GAM theory. Moreover, the different non-interactions between the GAMs and AT at the generating position and the propagating positions have also been identified. The results indicate that GAM mainly gain energy from AT through amplitude modulation at the generating position, while at the propagation positions, AT would be mainly suppressed through the shearing effect of GAM. By the end of the paper, we discussed the discharging condition of dual GAMs. Our results provided direct proofs that the collision damping rate is the key factor to generate the dual GAMs.

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