Simulation Study of A New Kind of Energetic Particle Driven Geodesic Acoustic Mode

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A new kind of energetic particle driven geodesic acoustic mode (EGAM) is investigated using a hybrid simulation code for energetic particles interacting with a magnetohydrodynamic fluid. The energetic particle charge exchange and inertia are considered, and the new EGAM, which has weak bulk plasma temperature dependence of frequency in LHD, is reproduced by simulation. By contrast, the traditional EGAM frequency is proportional to the square root of bulk plasma temperature. Three conditions are found to be important for the transition from the traditional EGAM to the new EGAM: 1) high energetic particle pressure, 2) high charge exchange rate, and 3) low bulk plasma density. A new resonance condition that $\omega_{EGAM} = (l/K)\omega_\theta$ is obtained, where l and K are arbitrary integers. l/K = 2/3 and l/K = 3/5 for most counter- and co-going particles, respectively. The counter-going particles are more dominant for resonance. In addition, it is found that the new EGAM is a kind of typical energetic particle mode (EPM).

A new kind of energetic particle driven geodesic acoustic mode (EGAM), which has weak bulk plasma temperature dependence of frequency, has been found in the Large Helical Device (LHD) experiments [1-2] as shown in Fig. 1. In this work, the new kind of EGAM is investigated with a hybrid simulation code for energetic particles and magnetohydrodynamics (MHD). It is demonstrated in Fig. 2 that the new EGAM in the simulation results has weak bulk plasma temperature dependence of frequency, which is in contrast to the traditional EGAM whose frequency is proportional to the square root of bulk plasma temperature [3-4]. Three conditions are found to be important for the transition from the traditional EGAM to the new EGAM: 1) energetic particle pressure substantially higher than the bulk plasma pressure, 2) charge exchange rate sufficiently higher than the slowing down rate to create a bump-on-tail type distribution, and 3) bulk plasma density is low enough.

MEGA code [5] is used to simulate the EGAMs in LHD. Since the kinetic geodesic acoustic mode frequency in LHD [6] is close to that in tokamaks, we investigate tokamak type equilibria with concentric circular magnetic surfaces, and with the safety factor profiles and the aspect ratio similar to the LHD plasmas. The tokamak type equilibrium is a

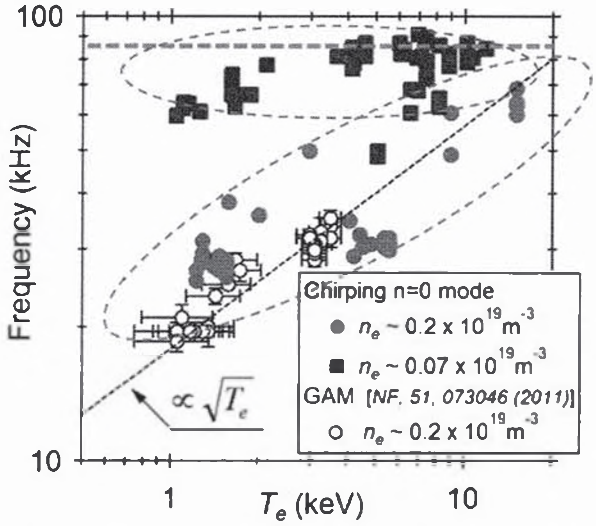

Figure 1. The new EGAM (blue) and traditional EGAM (red and black) in experiment. This figure is from Ref. [1] and [2].

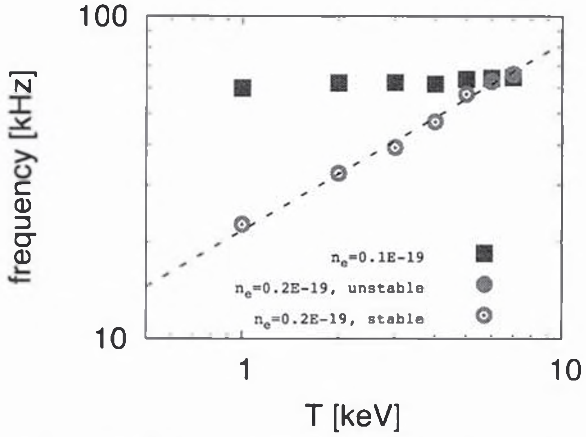

Figure 2 Two kinds of EGAMs are simulated with β_h=3% and τ_{cx}=0.39s. The bulk plasma densities for new (squares) and traditional EGAMs (circles) are $10^{18}m^{-3}$ and $2\times10^{18}m^{-3}$, respectively. The open circles represent stable mode.

reasonable approximation, because we found in our previous work [4,7] that the resonance with EGAM takes place for passing particles. The energetic particle distribution function is characterized by the slowing down time τ_s (=8s in this work) and charge exchange rate ν_{cx} . For high ν_{cx} value, the distribution function has a bump-on-tail shape. The energetic ion inertia term is added into the MHD momentum equation to simulate with energetic particle density comparable to the bulk plasma density. In addition, a Gaussian-type pitch angle distribution is assumed for the energetic ions.

Both the new and traditional EGAMs are reproduced with simulation parameters based on the LHD experiment [1-2], as shown in Fig. 2. The parameters are magnetic field strength B=1.5T, NBI energy E_{NBI}=170keV, energetic particle beta value β_h=3%, and $\nu_{cx}=2.5s^{-1}$. For electron density $n_e=10^{18}m^{-3}$, the new EGAM has weak bulk plasma temperature dependence of frequency. On the other hand, for electron density $n_e=2\times10^{18}m^{-3}$, the traditional EGAM is excited with the frequency proportional to the square root of bulk plasma temperature. The simulated phenomena are very similar to the experimental observation that is shown in Fig. 1.

The resonance condition of the new EGAM is investigated. Normally, when a resonant particle passes one round in the poloidal angle, the phase of the mode should change by a multiple of 2π, then the resonance condition is given by $\omega_{mode}T_\theta - n\Delta\varphi = 2\pi l$, where T_θ is the time to pass one round in the poloidal angle, n is toroidal mode number, $\Delta\varphi$ is the toroidal angle, and l is an arbitrary integer. [8] But the new EGAM case is special. When a resonant particle passes not one round but K rounds in the poloidal angle, the resonance condition is given by $K\omega_{EGAM}T_\theta - Kn\Delta\varphi = 2\pi l$, where K is arbitrary integer. n = 0 for GAM, so the resonance condition is $\omega_{EGAM} = (l/K)\omega_\theta$, where $\omega_0 = 2\pi/T_\theta$. In order to confirm that, the particle which resonates strongest with mode, that means the particle with maximum δf value, is selected from all the half a million particles, and investigated. This particle is counter-going, and $\omega_\theta/(2\pi)$ = 85kHz. The evolution of particle position in z direction is plotted as red curve in Fig. 3(a). When the particle cross the mid-plane, the z value becomes 0, and that means particle moves a half period in poloidal cross section. We also plot the deformed mode amplitude v_θ as blue curve, where deformed v_θ is $v_\theta e^{-\gamma t}$. In Fig. 3(a), particle moves 3 circles while mode oscillates 2 times in the time interval between the 2 black lines, so l/K = 2/3. According to resonance condition, $\omega_{EGAM}/(2\pi)$ = 57kHz, very close to the mode frequency 59kHz. In addition, the particle which is co-going and resonates strongest with mode is also selected and investigated. The

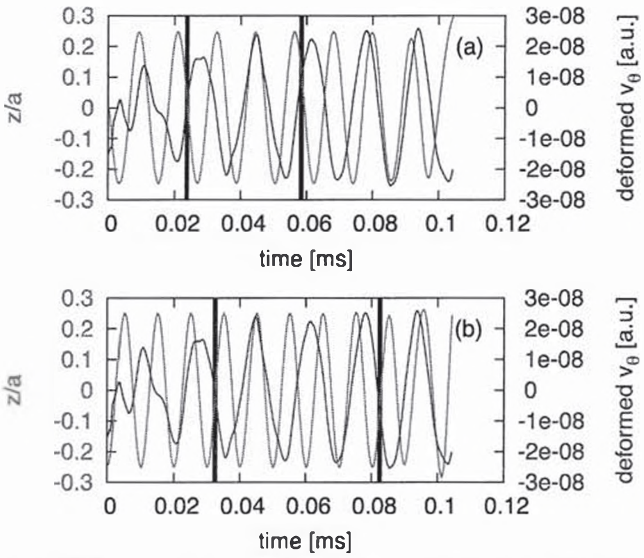

Figure 3 Time evolution of particle position in z direction and deformed amplitude v_θ for (a) the strongest resonant particle in counter-going direction and (b) co-going direction. The simulation condition is corresponding to the blue square with T = 4keV in Fig. 2.

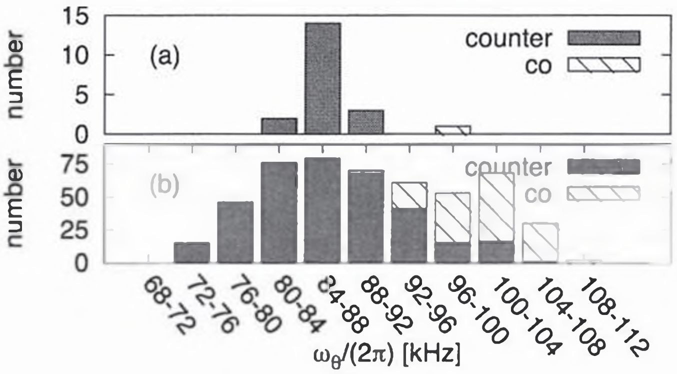

Figure 4 Statistics of the frequency distribution of (a) 20 particles and (b) 500 particles which resonate strongest with mode. Red region and blue shading represent counter- and co-going particles, respectively.

particle frequency $\omega_\theta/(2\pi) = 100$kHz. In Fig. 3(b), particle moves 5 circles while mode oscillates 3 times in the time interval between the 2 black lines, so $l/K = 3/5$. According to resonance condition, $\omega_{EGAM}/(2\pi) = 60$kHz, also close to the mode frequency 59kHz.

In fact, different particles have different l/K values. For confirmation, 20 particles and 500 particles which resonate strongest with mode are selected and analyzed, as shown in Fig. 4. In Fig. 4(a), most particles distribute in the range between 84kHz and 88kHz. Considering mode frequency 59kHz, we know most of particles have same l/K values that equal to 2/3. In Fig. 4(b), the conclusion is similar because the bar around 86kHz is also the highest. In addition, we find that most of co-going particles distribute around the frequency 100 kHz, that means they have same l/K values that equal to 3/5. Moreover, the counter-going particles (red) are more dominant for resonance, and it is consistent with DIII-D experiment [9].

Linear growth properties of the new EGAM are further investigated. Figure 5 shows that frequency increases as the central value of the Gaussian pitch angle distribution decreases, where smaller pitch angle variable corresponds to higher parallel velocity and higher transit frequency. This indicates that the frequency of new EGAM is significantly affected by the energetic particle transit frequency, and the new EGAM is a kind of energetic particle mode (EPM) whose frequency is determined by the energetic particles. Figure 6 shows the frequency dependence on β_h and ν_{cx}. Growth rate of new EGAM increases as β_h increases similarly with other energetic particle driven instabilities, but the frequency increases as β_h increases. For higher β_h, the effect of energetic particles is enhanced to make the frequency closer to the energetic particle transit frequency. In addition, higher ν_{cx} causes higher growth rate and frequency, because more particles exist in the high energy region of phase space.

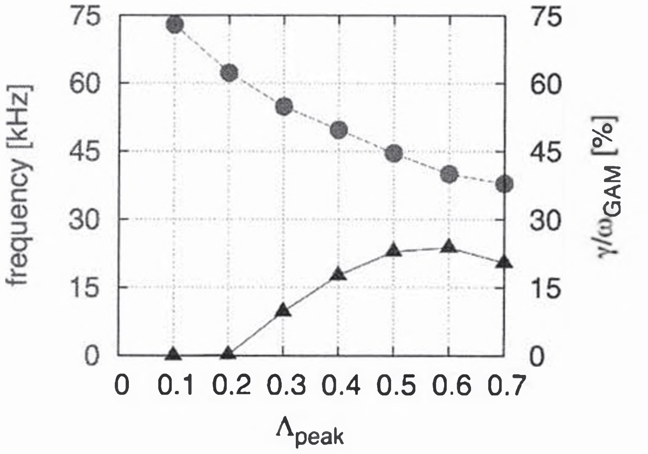

Figure 5. New EGAM frequency (circles) and growth rate (triangles) versus the center of pitch angle variable distribution Λ_{peak} with bulk plasma temperature 4 keV and density 10^{18}m^{-3}.

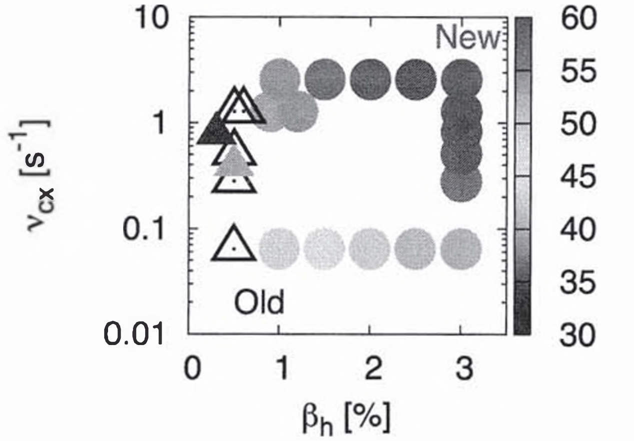

Figure 6. Mode frequency [kHz] is represented by color for various energetic particle beta and charge exchange rate. Circles represent unstable modes, and triangles are stable ones. The frequencies of open triangles are difficult to analyze.

In summary, we considered energetic particle charge exchange and inertia, and updated MEGA code to simulate the new EGAM which has weak bulk plasma temperature dependence of frequency in LHD. By contrast, the traditional EGAM frequency is proportional to the square root of bulk plasma temperature. The simulation results are consistent with experiments. The simulation parameters for EGAM excitation of both traditional and new EGAMs are compared and analyzed, and three conditions are found to be important for the transition from the traditional EGAM to the new EGAM: 1) energetic particle pressure substantially higher than the bulk plasma pressure, 2) charge exchange rate sufficiently higher than the slowing down rate to create a bump-on-tail type distribution, and 3) bulk plasma density is low enough. The resonant particles of new EGAM are investigated, and a new resonance condition, $\omega_{EGAM} = (l/K)\ \omega_\theta$, is obtained. Normally, K = 1 for energetic particle driven instabilities like Alfven eigenmodes, but K can be arbitrary integer for new EGAM, so the new resonance condition in the present work is a stronger form compared with the traditional one. l/K is 2/3 and 3/5 for most of counter- and co-going particles, respectively. In addition, we confirmed that the counter-going particles have stronger resonance than co-going particles, and it is consistent with DIII-D's experiment. Finally, the new EGAM frequency is affected by energetic particles indicating that the mode is a kind of typical EPM.

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Reference

[1] M. Osakabe, T. Ido, K. Ogawa *et al*, *13th IAEA-TM EP, 17-20 September 2013, Beijing, China.*
[2] T. Ido, M. Osakabe, A. Shimizu *et al*, *24th IAEA-FEC*, 8-13 October 2012, San Diego, USA.
[3] T. Ido, A. Shimizu, M. Nishiura *et al*, *Nucl. Fusion* **51**, 073046 (2011).
[4] H. Wang and Y. Todo, *Phys. Plasmas* **20** (2013) 012506.
[5] Y. Todo, *Phys. Plasmas* **13** (2006) 082503.
[6] H. Sugama and T.-H. Watanabe, *Phys. Plasmas* **13** (2006) 012501.
[7] H. Wang, Y. Todo and C. Kim, *Phys. Rev. Lett.* **110** (2013) 155006.
[8] Y. Todo and T. Sato, *Phys. Plasmas* **5** (1998) 1321.
[9] R. Nazikian *et al*, *Phys. Rev. Lett.* **101** (2008) 185001.