§2. Hole-Clump Pair Creation in the Evolution of Energetic Particle Driven Geodesic Acoustic Mode

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Geodesic acoustic mode (GAM) is an oscillatory zonal flow coupled with density and pressure perturbations in toroidal plasmas. Recently, energetic particle driven GAM (EGAM) and the frequency chirping is observed in JET, DIII-D, and LHD. In the DIII-D experiment, drops in neutron emission follow the EGAM bursts suggesting beam ion losses. Understanding EGAM is important for magnetic confinement fusion where the energetic particles need to be well confined for the bulk plasma heating.

A hybrid simulation code for energetic particles interacting with a magnetohydrodynamic (MHD) fluid, MEGA[1], is used for the simulation of EGAM [2]. In the MEGA code, the bulk plasma is described by the nonlinear MHD equations. The drift kinetic description and the δf particle method are applied to the energetic particles. The physics condition in the simulation is based on an LHD experiment, $B_0 = 1.5$ T, electron density $n_e = 0.1 \times 10^{19}$ m^{-3}, electron temperature at the magnetic axis $T_e = 4$ keV, bulk plasma beta value at the magnetic axis equals to 7.2×10^{-4}. The neutral beam injection energy is $E_{NBI} = 170$ keV [3].

EGAM frequency chirping takes place in the nonlinear phase, and the evolution of frequency spectrum and poloidal velocity is shown in Fig. 1. The mode frequency chirps up from 40 kHz to 50 kHz in 0.4 ms. Another branch chirps down, but this branch is weaker than the chirping up branch. The energetic particle δf distribution in two-dimensional velocity space (Λ, E) is shown for t = 0.51 ms, 0.80 ms, and 1.02 ms in Fig. 2(a)-(c), where blue color represents $\delta f < 0$ (hole) while red color for $\delta f > 0$ (clump). We see in the figure that two pairs of hole and clump are created along the constant μ curves in (Λ, E) space. One pair is created along the higher-μ curve with a hole in the high energy side and a clump in the low energy side. This pair is consistent with Berk-Breizman model [4] where a hole (clump) is created in the high (low) energy side. The other pair is created along the lower-μ curve in the stabilizing region. We see a clump in the high energy side and a hole in the low energy side. Solid curves in Fig. 2(a)-(c) represent the constant poloidal transit frequency. The transit frequencies of right hole and left clump are increasing, and they correspond to the chirping up branch in Fig. 1. On the other hand, the left hole and right clump shift to lower transit frequency and correspond to the chirping down branch. For more accurate comparison of the transit frequency with the EGAM frequency, the transit frequencies of the peak (=clump) and the bottom (=hole) of the perturbative distribution are mapped into Fig. 1(a). We see good agreement between the EGAM frequencies and the transit frequencies of the hole and the clump. This indicates

the particles comprising the hole and clump are kept resonant with the EGAM during the frequency chirping.

In summary, we have carried out the nonlinear simulations of EGAM, and found that spontaneous frequency chirping takes place and two hole-clump pairs are formed in the energetic particle distribution function in 2-dimensional velocity space of pitch angle variable and energy. One pair is formed in the phase space region that destabilizes the instability, while the other in the stabilizing region. The transit frequencies of particles in the holes and clumps are in good agreement with the chirping EGAM frequency indicating that the particles are kept resonant with the EGAM during the nonlinear frequency chirping. We would like to emphasize that we have found the hole-clump pairs in a more realistic system than that investigated in Ref. [4]. Our results indicate that the double phase space structure of stabilizing and destabilizing particles is ubiquitous for the spontaneous frequency chirping phenomena.
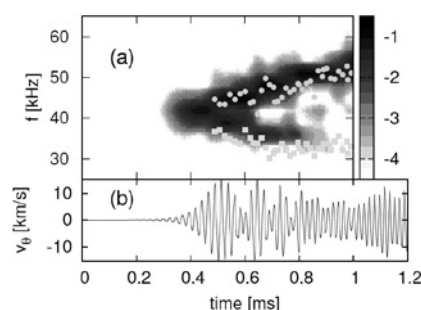

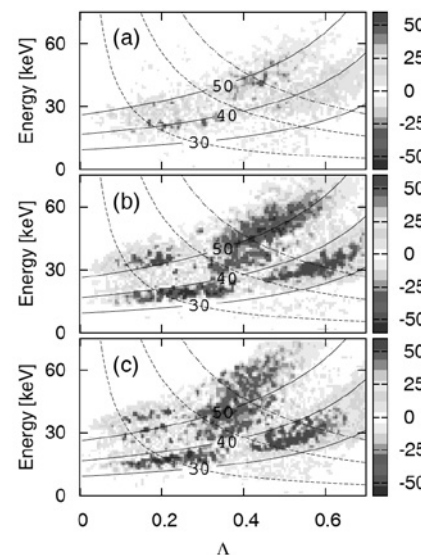Figure 1. Time evolution of (a) EGAM frequency spectrum and (b) poloidal velocity.

Figure 2. Energetic particle δf distribution

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2) Wang, H. *et al*., Phys. Rev. Lett **110**, 155006 (2013)
3) Ido, T. *et al*., Nucl. Fusion **51**, 073046 (2011)
4) Berk, H. L. *et al*., Phys. Plasmas **6**, 3102 (1999)