S4-3

トロイダルプラズマにおける高速イオン励起振動帯状流のダイナミクス
Dynamics of energetic particle-driven oscillatory zonal flow in toroidal plasmas

井戸　毅
Takeshi Ido

九州大学応用力学研究所
Research Institute for Applied Mechanics, Kyushu University

High-temperature plasmas for nuclear fusion research often include not only thermalized plasmas, but also energetic particles, such as alpha particles produced as a result of the D-T reaction, and energetic particles from beams injected to heat the plasmas. The energetic particles have different pressure profiles and velocity distributions from those of thermalized plasmas. Their pressure gradient in the real space and inverse gradient in the velocity space can excite various instabilities. The energetic-particle driven instabilities cause energetic-particle loss, which deteriorates the heating efficiency of the plasma by energetic particles, and consequently deteriorates the performance of the fusion reactors. Thus, the investigation of energetic-particle driven instabilities is crucial for the development of fusion reactors. On the other hand, the energetic particles cause various nonlinear phenomena and spatiotemporal patterns, and they show us interesting phenomena. In this talk, characteristic phenomena related to energetic-particle driven geodesic acoustic mode (EGAM)[1], which is a kind of energetic-particle driven instabilities and an oscillatory zonal flow in toroidal plasmas, are presented.

Zonal flows are driven through nonlinear coupling of turbulence in magnetically confined plasmas, and the density fluctuation and the electric potential fluctuation associated with the zonal flows are uniform in both the toroidal and poloidal directions. In toroidal plasmas, due to the deviation of the magnetic field lines from the geodesics curve, $\boldsymbol{E}_r \times \boldsymbol{B}$ flow, where $\boldsymbol{E}_r$ is the radial electric field and $\boldsymbol{B}$ is the magnetic field, causes compression (or rarefaction) at the top of the torus and rarefaction (or compression) at the bottom of the torus. The resulting up-down antisymmetric density induces the restoring force, and the zonal flow oscillates. This oscillatory zonal flow is called geodesic acoustic mode (GAM). The spatial structure of the GAM is uniform in the toroidal direction like static zonal flow, but the poloidal structure of the electric potential fluctuation is uniform, and the poloidal structure of the density fluctuation is up-down antisymmetric unlike the static zonal flow. Because the wave number of the GAM parallel to the magnetic field is non-zero, the GAM can interact with particles through Landau damping. When energetic particles in plasmas have a positive gradient in the velocity space, they can drive the GAM, and the GAM is called EGAM.

In Large Helical Device (LHD), the electric potential fluctuation, density fluctuation, and magnetic field fluctuation associated with the EGAM have been observed, and the spatial structures have been confirmed to be the same as those of the GAM[2]. Simultaneously, creation of a hole and a clump corresponding to the inverse Landau damping have been observed in the energy distribution function of ions, and it has been experimentally demonstrated that the GAMs are excited by fast ions[3].

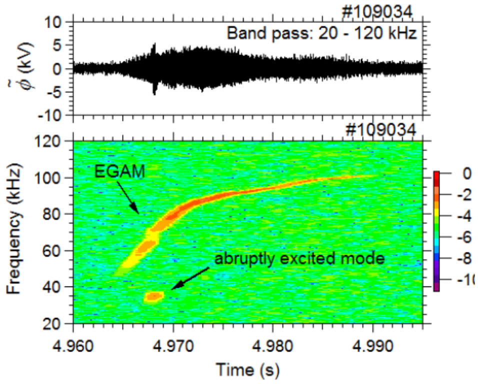

FIG. 1 Electric potential associated with EGAM and GAM (top) and its spectrogram(bottom). An intense GAM is abruptly excited at 4.968 s.

The structures in the energy distribution function representing the wave-particle interaction evolve in time, and the frequency upchirps correspondingly. When the up-chirping frequency reaches twice the ordinary GAM frequency, another GAM is sometimes excited with a large amplitude abruptly and transiently[4,5], as show in Fig. 1. The existent position, frequency, and phase relation of the abruptly excited GAM and EGAM strongly suggest the mode coupling between EGAMs and GAMs. This mode coupling is reproduced by numerical simulation[6].

The relation between the amplitude and the growth rate shows a nonlinear evolution of the abruptly excited GAM (Fig. 2). In general, the growth rate decreases monotonically as the amplitude because the driving source is consumed by the mode excitation. In contrast, in the case in which the GAM is strongly excited, although the growth rate decreases monotonically for small amplitudes, it increases with an increasing amplitude when the amplitude exceeds a threshold of approximately 2 μT. This abrupt and nonlinear evolution can be interpreted as the excitation of subcritical instability of the GAM triggered by the EGAM[7,8]. Since a subcritical instability is one of the working hypotheses of the onset of abrupt phenomena such as sawtooth oscillation and disruption in laboratory plasmas, as well as solar flares in astro-plasmas, this observation and analysis demonstrate an example of experimental paths for exploring the trigger problem of abrupt phenomena.

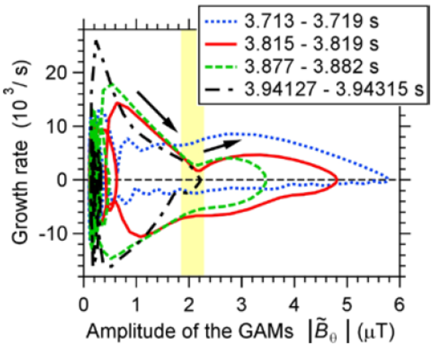

FIG. 2 Amplitude dependence of growth rate. Four different bursts are plotted.

Although the EGAM is excited by the energetic particles, it is theoretically pointed out that the EGAM may have significant impacts on the transport of the bulk plasma.

One of the impacts is the trapping of turbulence by the second derivative of the flow associated with the EGAM[9,10]. Since the EGAM propagates in the minor radius direction, the turbulence trapped by the EGAM can propagate even across the transport barrier. Thus, the turbulent transport can be modified by the EGAM.

Another interesting impact on the bulk plasma is a possible heating of bulk ions by the EGAM. The mechanism is called GAM channeling[11], and it is a kind of alpha channeling[12] which is expected to heat bulk ions directly via waves excited by energetic alpha particles in fusion reactors. Since the EGAM is excited through the inverse Landau damping by fast ions with velocities comparable to the phase velocity, the absorbed power by slower bulk ions is not large[13]. However, if the resonance between the radial propagation of the EGAM and the toroidal drift motion of bulk ions occurs, the wave form of the EGAM is deformed around the resonance location. The deformation increases the wave number and decreases the phase velocity of the EGAM, which leads to an increase in the absorbed power through the Landau damping by the bulk ions[14]. In LHD, an increase in the energy is sometimes observed in the low energy region of the ion energy distribution function during the burst of the EGAM[3]. Although the phenomenon is still under investigation, it may correspond to the theoretical prediction above.

Acknowledgements

The author appreciates Dr. A. Shimizu, Dr. M. Nishiura, and LHD experiment group for the collaboration for the LHD experiment. The author also thanks Dr. M. Lesur of Universite de Lorraine, Dr. M. Sasaki of Nihon Univ., Dr. H. Wang, Prof. Y. Todo, Prof. Osakabe of NIFS, Prof. K.Itoh of Chubu University for valuable discussion.

This work was supported by MEXT Japan under Grant-in-Aid for Scientific Research (C) (No.18K03589), by NIFS/NINS under NIFS20KLPH046 and NIFS20KUTR147, and by JSPS under KAKENHI Grant Nos. JP17H06089, JP18K03589, and Advanced Core-to-Core Network Program 'PLADyS'.

Reference

[1] Fu G Y, 2008 Phys. Rev. Lett. 101 185002
[2] Ido T, et al., 2015 Nucl. Fusion 55 83024
[3] Osakabe M, et al., Proc. 25th IAEA Fusion Energy Conf. Ex/10-3
[4] Ido T, et al., 2016 Phys. Rev. Lett. 116 15002
[5] Ido T, et al., 2017 Nucl. Fusion 57 72009
[6] Wang H, et al., 2018 Phys. Rev. Lett. 120 175001
[7] Lesur M, et al., 2016 Phys. Rev. Lett. 116 15003
[8] Lesur M, et al., 2016 Nucl. Fusion 56 56009
[9] Zarzoso D, et al., 2013 Phys. Rev. Lett. 110 125002
[10] Sasaki M, et al., 2017 Sci. Rep. 7 16767
[11] Sasaki M, et al.,2011 Plasma Phys. Control. Fusion 53 85017
[12] Fisch N J et al., 1994 Nucl. Fusion 34 1541
[13] Wang H, et al., 2020 Nucl. Fusion 60
[14] Sasaki M, et al., 2016 Phys. Plasma 23