§3. Properties of Energetic-particle Continuum Modes Destabilized by Energetic Ions with Beam-like Velocity Distributions

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Properties of energetic-particle continuum modes (EPM) in tokamak plasmas were investigated using the hybrid simulation code for magnetohydrodynamics and energetic particles, MEGA [1]. It was theoretically predicted that EPMs have frequencies in the range of characteristic energetic-particle frequencies such as transit, bounce, and precession frequencies [2]. The purpose of this work is to investigate the EPM spatial profile for various energetic –ion velocity and to compare carefully the EPM frequency with the energetic-ion orbital frequency. The energetic ions were assumed to have beam-like velocity distributions for the purpose of clarifying the dependence on energetic ion velocity. We focused on the unstable modes with toroidal mode number n=1.

It was found that the unstable modes are EPMs for the beam velocities lower than the Alfvén velocity while the toroidal Alfvén eigenmodes (TAE) are unstable for the beam velocities well above the Alfvén velocity. For the safety factor profile investigated, the primary poloidal harmonic of the EPMs destabilized by the co-passing energetic ions is m=2 while they are m=1 for the counter-passing energetic ions. This difference was explained by the resonance condition between the energetic beam ions and the EPMs.

Next, we focus on EPMs destabilized by co-passing energetic ions in order to compare the EPM frequency carefully with the energetic-ion orbital frequency. We chose a safety factor profile $q = 1.35 + 1.65(r/a)^2$ where a is the minor radius and r is the radial coordinate. The energetic ion beta value at the plasma center is $\beta_{h0} = 1\%$. For toroidal mode number n=1, a shear Alfvén continuous spectrum gap is located at r/a=0.3 and q=1.5.

In Fig. 1, we show the frequencies and peak locations of the unstable modes destabilized by co-passing energetic ions with different beam velocities. The beam velocity is denoted by v_0, and v_A is the Alfvén velocity. It is interesting to note that the peak locations are close to the Alfvén continuous spectrum. We see that the modes destabilized by faster energetic-ions have higher frequency. We compare the following energetic-ion orbital frequency

$$\omega_E = \frac{v_0}{R_0}\left(\frac{n}{1+\sigma} - \frac{l}{q}\right)$$

with the frequency of the unstable modes. Here, R_0 is the plasma major radius and l is an arbitrary integer. The correction term $\sigma \equiv q v_0 m_h / Z_h e B_0 R_0$ appears from a fact that the center of the beam ion orbits shifts from the plasma center by σR_0, where B_0 is the magnetic field intensity at the plasma center, and m_h and $Z_h e$ are energetic-ion mass and charge. For q=1.4 and $v_0 = v_A$, the correction term is σ=0.03. This term gives a correction of roughly 10% to the energetic-ion orbital frequency ω_E. In Fig. 2, we plot the frequencies of the unstable modes and the energetic-ion orbital frequency versus the beam velocity v_0. The energetic-ion orbital frequency in Fig. 2 is calculated assuming a constant safety factor value q=1.4 and $l = 1$. This is a reasonable assumption since the perturbed energetic-ion pressure peaks near the plasma center where the magnetic shear is weak, and the dominant poloidal harmonic of the perturbed energetic-ion pressure is m=1. We see that the mode frequency ω is in good agreement with the energetic-ion orbital frequency ω_E. The results shown in Fig. 2 demonstrate that the frequency of the unstable modes is determined by the energetic-ion orbital frequency and the unstable modes for the beam velocities $v_0 \le 1.2 v_A$ are the energetic-particle continuum modes. Thus, we can conclude that the energetic-ion orbital frequency determines the EPM frequency.

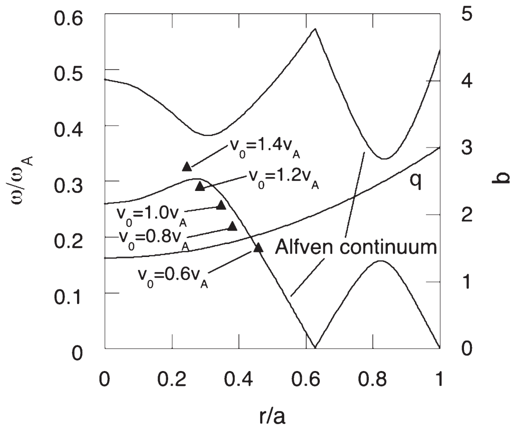

Fig. 1. Frequencies and peak locations of the unstable modes destabilized by co-passing energetic ions with different beam velocities are represented by triangles. Also shown are the safety factor (q) profile and the shear Alfvén continuous spectra with toroidal mode number n=1.

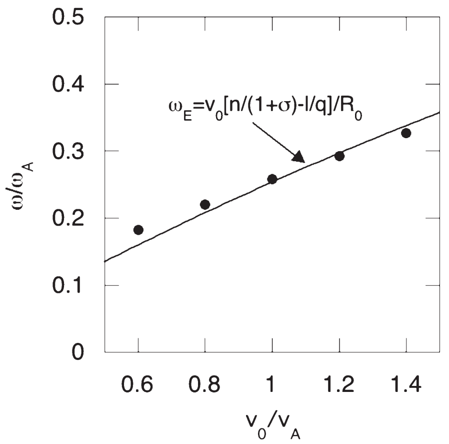

Fig. 2. Comparison between the energetic-ion orbital frequency (solid line) and the frequencies of the unstable modes (circles).

[1] Y. Todo, Phys. Plasmas **13**, 082503 (2006).
[2] L. Chen, Phys. Plasmas **1**, 1519 (1994).