Rapid Communications

Computer Simulation of Frequency Sweeping of Energetic Particle Mode in a JT-60U Experiment

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(Received 19 September 2003 / Accepted 9 October 2003)

Fast frequency sweeping (fast FS) mode in a JT-60U plasma is investigated with particle-magnetohydrodynamic hybrid simulation. A new kind of energetic particle mode (EPM) is found near the plasma center at a frequency close to the central frequency of the fast FS mode. Frequency sweeping close to that of the fast FS mode takes place. The ratio of the mode damping rate to the linear growth rate is consistent with spontaneous hole-clump pair creation.

Keywords:
fast frequency sweeping mode, energetic particle mode, computer simulation, JT-60U

Instabilities with frequency sweeping in the frequency range of Alfvén eigenmodes have been found with negative ion based neutral beam (NNB) injection in JT-60U [1]. One type of instability, which is called the fast frequency sweeping (fast FS) mode, appears at frequency inside the toroidal Alfvén eigenmode (TAE) gap [2]. Frequency shifts rapidly by 10–20 kHz in 1–5 ms both upward and downward. Since the plasma profile changes in a much longer time scale, some non-linear effects of the interplay between the mode and the energetic ions created by the NNB injection must play an essential role in fast frequency sweeping.

Using the experimental q-profile, bulk pressure profile, and density profile of discharge E36379 [1], particle-magnetohydrodynamic (MHD) hybrid simulation [3] was carried out. In this simulation, the plasma is divided into two parts, namely, energetic ions and bulk plasma. The bulk plasma and the electromagnetic field are described by the MHD equations. This approximation is reasonable under the condition that the energetic ion density is much lower than that of the bulk plasma. For energetic ions, the drift-kinetic description was employed. To complete the equation system in a self-consistent way, we took account of energetic ion effects on bulk plasma in the MHD momentum equation. The δf particle simulation method was applied to the energetic ions. The major and minor radii are R_0 = 3.4 m and a = 1.0 m, respectively. The plasma shape in the simulation is circular while the shape in the ex-periment was divertor-shaped. The magnetic field at the magnetic axis is 1.2 T. The bulk plasma and the beam ions are deuterium. NNB injection energy is 346 keV. Initial energetic ion distribution in the velocity space is assumed to be a slowing down distribution. The perpendicular velocity of energetic ions is neglected because the NNB injection is tangential. The maximum velocity is assumed to be 80% of the injection velocity as the injection is not completely parallel to the magnetic field. This maximum velocity in simulation corresponds roughly to the Alfvén velocity at the magnetic axis.

A classical distribution which is formed by NNB injection and collisions (slowing down and pitch angle scattering) was calculated using the OFMC code [4]. The classical distribution, however, gives an overestimate of the energetic ion pressure and its gradient because in the experiments energetic ion loss and redistribution take place due to fast FS mode and another type of instability called abrupt large event with time intervals much shorter than the slowing down time. We have only limited information on energetic ion distribution in the experiments. In this study the initial energetic ion pressure, which is shown in Fig. 1(a), is assumed to be 1/5 of the classical distribution. We think

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that the energetic ion drive to the instability can be reduced to 1/5 by the redistribution due to recurrent fast FS modes although the factor 1/5 might be too small for stored beam energy. When the classical distribution is assumed for the initial condition, the linear growth rate is greater and frequency sweeping does not take place, while the linear unstable mode spatial profile and frequency are similar to those with the reduced pressure which are reported in this article. The number of particles used is 5.2×10^5. The viscosity and resistivity used in the simulation are both 10^{-5} normalized by the Alfvén velocity, major radius, and vacuum magnetic permeability.

An energetic particle mode (EPM) with frequency of $0.25\omega_A$ is destabilized where ω_A is the Alfvén frequency at the plasma center. This frequency is close to the central frequency of fast FS mode ~50 kHz which is $0.24\omega_A$. Figure 1(b) shows the frequency and location of the EPM. In Fig. 1(b) also shown are the q-profile and the $n = 1$ shear Alfvén continuous spectra. Figure 2 shows the spatial profile of the cosine and sine part of the EPM electrostatic potential. In Fig. 2, phase is chosen so as to maximize the cosine part amplitude. The primary poloidal/toroidal mode number is $m/n = 2/1$. Deviation of the mode location from the TAE gap at r/a~0.8 supports that this mode is not a TAE but an EPM. We have confirmed that spatial profile and frequency depend on the initial energetic ion pressure profile. EPM frequency seems to be chosen inside the TAE gap so that the continuum damping is minimized. On the other hand, TAE modes which probably exist at r/a~0.8 at frequencies inside the TAE gap, are not destabilized due to the small energetic ion pressure there. The EPM found in the simulation is different from the local EPM [5,6] but similar to the nonlocal EPM which is predicted for ICRF heated plasma with reversed magnetic shear [7]. Theoretical exploration is needed to clarify the properties of the EPM with passing energetic ions and monotonic shear.

Nonlinear evolution is investigated until $\omega_A t$ = 3,000 which corresponds to 2.4 ms. The time evolution of the toroidal electric field frequency spectrum is shown in Fig. 3. The contour levels are 0.19, 039, and 0.59 of the maximum value. It is found that the frequency shifts upward by 8% (~4 kHz) and downward by 17% (~9 kHz) of the frequency in the linear growth phase. These frequency shifts are close to those of the fast FS mode. Frequency upshift and downshift due to spontaneous hole-clump pair creation in a phase space was found by simulating a reduced kinetic equation

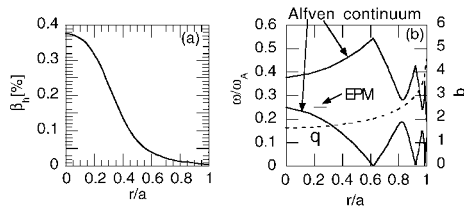

Fig. 1 (a) Initial energetic ion beta profile. (b) Frequency and location of the EPM with the q-profile and the n = 1 shear Alfvén continuous spectra.

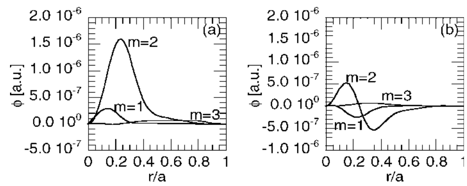

Fig. 2 Spatial profile of (a) the cosine part and (b) the sine part of the EPM electrostatic potential.

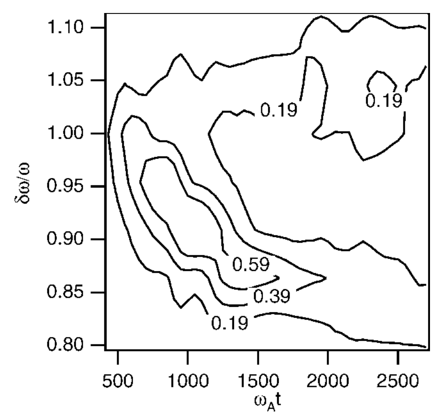

Fig. 3 Time evolution of the toroidal electric field frequency spectrum. Contour levels are 0.19, 0.39, and 0.59 of the maximum value.

when the linear damping rate (γ_d) is greater than 0.4 of the linear growth rate without damping (γ_L) [8]. In the present simulation, the ratio γ_d/γ_L is 0.68. This is consistent with the spontaneous hole-clump pair creation.

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