Kinetic-Magnetohydrodynamic Simulation Study of Fast Ions and Toroidal Alfvén Eigenmodes

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Abstract

Particle-magnetohydrodynamic and Fokker-Planck-magnetohydrodynamic simulations of fast ions and toroidicity-induced Alfvén eigenmodes (TAE modes) have been carried out. Alpha particle losses induced by TAE mode are investigated with particle-magnetohydrodynamic simulations. Trapped particles near the passing-trapped boundary in the phase space are also lost appreciably in addition to the counter-passing particles. In Fokker-Planck-magnetohydrodynamic simulation source and slowing-down of fast ions are considered. A coherent pulsating behavior of multiple TAE modes, which occurs in neutral beam injection experiments, is observed when the slowing-down time is much longer than the damping time of the TAE modes and the fast-ion pressure is sufficiently high. For a slowing-down time comparable to the damping time, the TAE modes reach steady saturation levels.

1. INTRODUCTION

The toroidicity-induced Alfvén eigenmode (TAE mode) is a shear-Alfvén eigenmode in toroidal plasmas [1]. TAE modes have been observed in many experiments such as the neutral beam injection (NBI) experiments [2, 3], the ion-cyclotron-range-of-frequency (ICRF) heating experiments [4, 5], and D-T fusion experiments at TFTR [6]. Nonlinear evolution of TAE modes is an important issue for fusion reactors, since TAE modes of sufficiently large amplitude can induce fast-ion losses [3, 7]. The first purpose of the present paper is to investigate the TAE-induced fast ion losses with particle-magnetohydrodynamic (MHD) simulation [8]. The second purpose is to examine the pulsating behavior of multiple TAE modes in NBI experiments, which is completely different from the steady behavior of ICRF-driven and alpha-driven TAE modes. It is investigated with Fokker-Planck-MHD simulation [9].

2. PARTICLE-MHD SIMULATION

In the particle-MHD simulation [8], the particle simulation method is used for the fast ions. In the model employed here, plasma is divided into two parts, the background plasma and fast ions. The background plasma is described by the magnetohydrodynamic (MHD) equations and the electromagnetic field is given by the MHD description. This approximation is reasonable under the condition that the fast ion density is much less than the background plasma density.

The initial condition considered here is $B=5$T, $I_p=2$MA, $R_0=2.7$m, $a=0.9$m, $n=10^{20}$m^{-3}, and $<\beta>=0.88\%$. Fast ion distribution is a slowing-down distribution with the maximum energy of 3.5 MeV, which is isotropic in the velocity space. Nonlinear simulations for $n=2$ TAE modes have been carried out for volume-average fast-ion pressures of 0.33% and 0.66%. The number of used particles is 4×10^6. Fast ion losses induced by the TAE modes are observed. For the higher-pressure case, 1% of fast ions are lost in 10^3 Alfvén time. Lost particles can be classified into three types; 1) passing particles with negative parallel velocities (counter-passing particles) which cross the passing-trapped boundary just before an encounter with the wall, 2) trapped particles, 3) passing particles other than the first type. Percentages to the total number of lost particles are 63%, 26%, and 11%, respectively. It is clear that counter-passing particles are the major part of lost particles and the main loss mechanism is crossing the passing-trapped boundary in the phase space. It is consistent with the results of test particle simulation in Ref. [10]. It must be noted, however, that the trapped particles near this boundary are also lost appreciably in addition to the counter-passing particles.

3. FOKKER-PLANCK-MHD SIMULATION

3.1. Model

Past simulation studies of TAE mode [11-14] started each simulation runs from arbitrarily chosen fast-ion distributions, and could not explain the recursive bursts at NBI heating experiments and steady saturation levels at ICRF heating experiments. Berk and Breizman [15] pointed out the significance of distribution forming processes such as particle source, slowing down, pitch-angle scattering, and wave heating. What seems to be lacking in the past simulation studies is to incorporate the distribution forming processes of fast ions.

As a first step towards a comprehensive simulation of TAE modes, we incorporate particle source and slowing down for fast ions in the Vlasov-MHD simulation code [12]. The time evolution of the fast-ion distribution function in a four-dimensional phase space (three-dimensional configuration space and one-dimensional velocity space for the parallel velocity) is followed by a finite difference method of fourth-order accuracy in space and time. The pitch-angle scattering and wave heating are not considered in the present study. We consider a four-dimensional phase space (R, φ, z, v), where v is the parallel velocity and (R, φ, z) are the cylindrical coordinates. Although only the parallel velocity component is taken into account for simplicity, the Jacobian for the three-dimensional velocity space is employed to be consistent with the slowing-down term. The critical velocity in the slowing down term and the birth velocity of fast ions are chosen to be equal to 0.3 and 1.5 of the Alfvén velocity, respectively. The spatial profile of the particle source is a Gaussian with the scale-length of $0.4a$, where a is the minor radius. We introduce two parameters, P_0, which is the fast-ion pressure at the magnetic axis when any MHD disturbance is absent, and the slowing down time τ_s. The initial condition is a tokamak MHD equilibrium where the aspect ratio is 3. The minor radius is 16 times larger than the parallel Larmor radius of a fast ion with the Alfvén velocity. In this paper a finite viscosity of $2\times10^{-5}R_0v_A$ is considered to damp TAE modes. It yields, for example, an e-folding damping time of $130\tau_A$ for an $n=2$ TAE mode which is the most unstable TAE mode in the results described below.

3.2. Results

3.2.1. Case A: P_0 = 2% (normalized by the magnetic pressure) and $\tau_s = 100\tau_A$

In this case the slowing-down time is comparable to the damping time. Destabilized are TAE modes with the toroidal mode numbers from 1 to 3, and another Alfvén eigenmode with the toroidal mode number of 4, which has a doubled frequency to that of a TAE mode. Time history of $m/n = 2/1, 3/2, 4/3, 6/4$ harmonics is shown in Fig. 1(a). The $n=2$-4 eigenmodes are localized in the core region. It can be seen that $n=2$-4 modes reach roughly steady saturation levels after $500\tau_A$.

3.2.2. Case B: P_0 = 4% (normalized by the magnetic pressure) and $\tau_s = 1000\tau_A$

In this case the slowing-down time is much longer than the damping time and the fast-ion pressure is relatively high. TAE modes with toroidal mode numbers from 1 to 4 are destabilized. The spatial profiles of $n=3$ and 4 eigenmodes peak at outer locations and are more broadened in the radial direction than those in case A. Time history of $m/n = 2/1, 3/2, 4/3, 6/4$ harmonics is shown in Fig. 1(b). It can be seen that they have a pulsating behavior. The spatial profile of the fast-ion source destabilizes the $n=2$ TAE mode first. Later than this precursory growth of the $n=2$ TAE mode, the other TAE modes grow to levels comparable to that of the $n=2$ TAE mode. At the second and third bursts, all of the TAE modes behave coherently. This pulsating bursts can be naturally interpreted as a cycle of reformation of fast-ion distribution, growth of TAE modes due to increasing fast-ion drive, global flattening of fast-ion distribution, and damping of TAE modes due to reduced fast-ion drive.

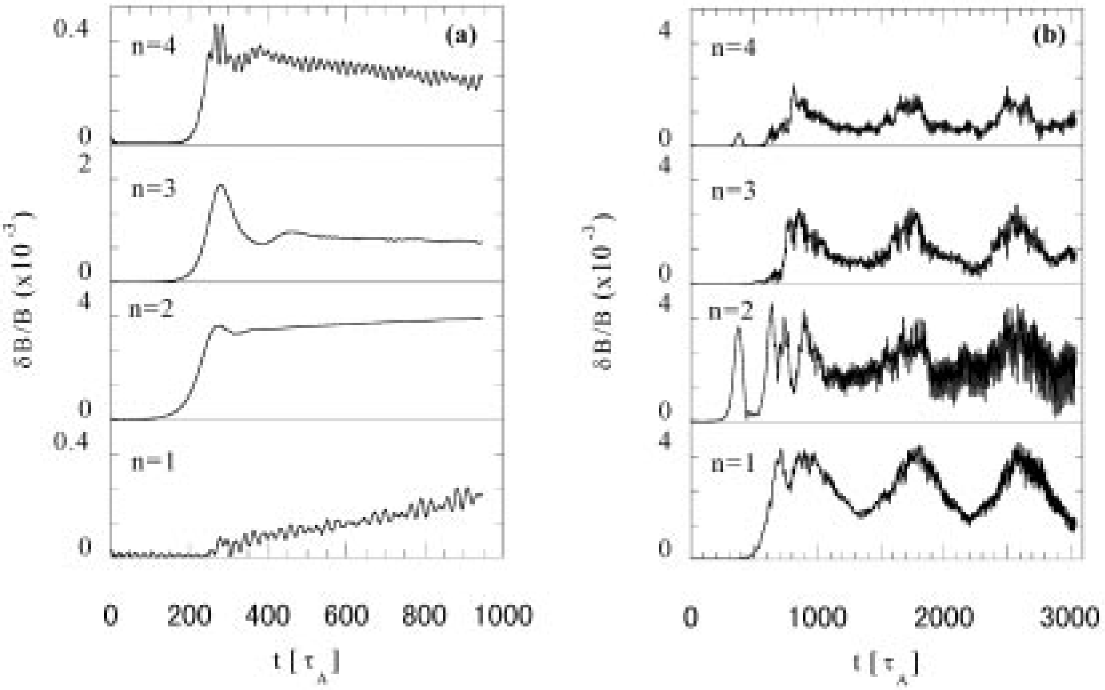

FIG. 1. Time evolution of n=1-4 TAE mode amplitudes for (a) P_0*=2% and* $\tau_s = 100\tau_A$*, and (b)* P_0*=4% and* $\tau_s = 1000\tau_A$*.*

3.2.3 Fast ion distribution at nonlinear phase

The fast-ion distribution is strongly affected by TAE modes. We show the fast-ion distribution averaged in the toroidal angle with $v = v_A$ in Fig. 2. For case A, the distribution is locally flattened in the core region where the TAE activity is strong. On the other hand, for case B, the *n=3* and *4* TAE modes, which spatially peak at outer locations as mentioned above, are destabilized, and the fast-ion distribution is globally flattened due to the overlapped many TAE modes. It is interesting to note that the distribution is spread close to the wall boundary at the mid-plane. It explains the fast-ion losses at the NBI experiments [3], which take place mainly at the mid-plane.

4. SUMMARY

In this paper we described the results of particle-MHD and Fokker-Planck-MHD simulations. With particle-MHD simulations, it is confirmed that the major part of lost alpha particles induced by TAE mode at the present large tokamaks is the counter-passing particles close to the passing-trapped boundary, and it is found that trapped particles are also lost appreciably. Furthermore, we have investigated the time evolution of fast ions and the toroidal Alfvén eigenmodes with the Fokker-Planck-MHD simulations. We have demonstrated that the consideration of the distribution forming processes of fast ions is crucial to understand the time evolution of TAE modes and fast ions.

Simulation results are summarized as follows:

[1] When the time scale of the distribution forming process [the slowing-down time in the present study] is comparable to the damping time, TAE modes persist after saturation with steady amplitudes.

[2] When the time scale of the distribution forming process is longer than the damping time and the fast-ion pressure is sufficiently high, many TAE modes have a coherent pulsating behavior.

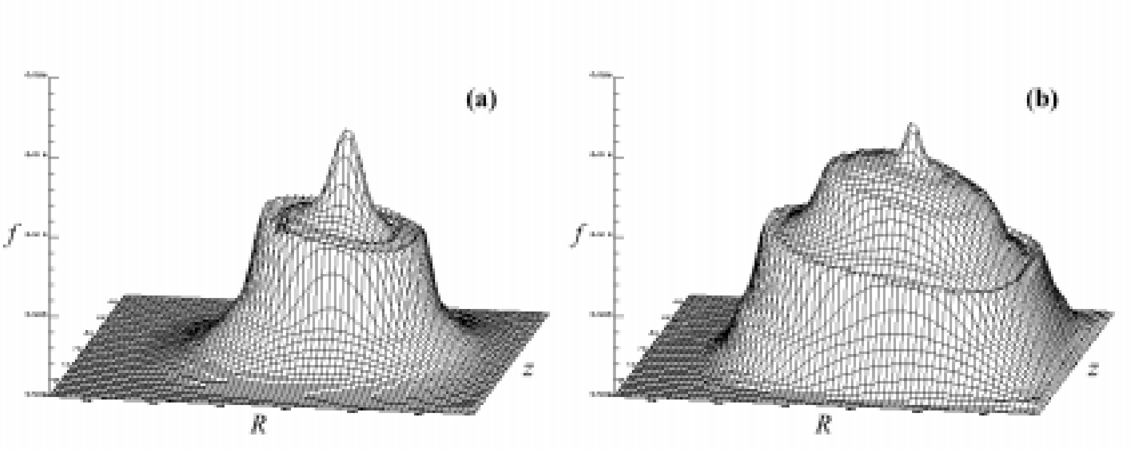

FIG. 2. Fast ion distribution as a function of R and z averaged in the toroidal angle with $v = v_A$ *for (a)* P_0*=2%,* $\tau_s = 100\tau_A$*,* $t=900\tau_A$*, and (b)* P_0*=4%,* $\tau_s = 1000\tau_A$*,* $t=2800\tau_A$*.*

The pulsating behavior is similar to that observed in NBI heating experiments. In this case, the fast-ion distribution function is globally flattened due to the overlapped many TAE modes. This global flattening explains the fast-ion losses observed at the NBI heating experiments. The steady saturation found for the short slowing-down time is also interesting when we compare it with the ICRF-driven and alpha-driven TAE modes, though a more realistic simulation is required for a detailed discussion.

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