CRITICAL FAST ION DISTRIBUTION IN PHASE SPACE FOR THE SYNCHRONIZED SUDDEN GROWTH OF MULTIPLE ALFVÉN EIGENMODES AND THE GLOBAL TRANSPORT OF FAST IONS

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Abstract

Alfvén eigenmodes (AEs) driven by fast ions in tokamak plasmas and the fast ion distribution formed with the AEs, neutral beam injection (NBI), and collisions are investigated with hybrid simulations for energetic particles and a magnetohydrodynamic (MHD) fluid. The multi-phase simulation, which is a combination of classical simulation and hybrid simulation, was applied for various beam deposition power ($P_{\text{beam}}$) and slowing-down time ($\tau_s$). In the classical simulation, energetic particle orbits are followed in the equilibrium magnetic field with NBI and collisions while the MHD perturbations are turned off. For the physical condition similar to a TFTR experiment [K. L. Wong et al., Phys. Rev. Lett. 66 (1991) 1874], the AE bursts take place with a time interval 2.7ms and the maximum MHD velocity $v/\nu_A=3\times10^7$, which are close to the TFTR experiment. With increasing volume-averaged classical fast ion pressure, the fast ion confinement degrades monotonically due to the transport by the AEs. The fast ion pressure profile resiliency, where the increase in fast ion pressure profile is saturated, is found for the cases with the AE bursts. The physical process of the AE burst in toroidal plasmas is clarified in the present paper. Before the AE bursts occur, multiple AEs become unstable, and grow to low amplitude. The low-amplitude AEs gradually and locally flatten the fast ion distribution in phase space leading to the formation of a stepwise distribution. The stepwise distribution is a “critical distribution” where the further beam injection leads to the higher AE amplitude, the broadening of the locally flattened regions, and their overlap. This resonance overlap of the multiple AEs [H. L. Berk, B. N. Breizman, and M. Pekker, Phys. Plasmas 2 (1995) 3007] brings about the AE burst, the global transport of fast ions, and the saturation of the distribution.

1. INTRODUCTION

The energetic-particle transport and losses brought about by Alfvén eigenmodes (AEs) are an important concern for burning plasmas. Rrecurrent bursts of AEs driven by beam fast ions have been observed in many tokamak and stellarator/heliotron plasmas [1-6]. Fast-ion losses associated with the AE bursts were indicated by the drop in neutron emission and the measurements with fast-ion loss detectors. Computer simulation is a powerful tool to investigate the interaction between AEs and energetic particles. However, we should notice that the energetic particle distributions in the experiments are formed in a longer time scale than the collisional slowing-down time for energetic particles interacting with the AEs. Then, comprehensive simulations that include the energetic particle source (birth of alphas, neutral beam injection, ion-cyclotron-range-of-frequency heating), collisions of energetic particles with the bulk plasma particles, energetic-particle losses, and the interactions between energetic particles and AEs are needed for the understanding of the energetic particle distribution in the experiments and the prediction of future experiments.

The author and his collaborators have developed such comprehensive simulations of energetic particles and AEs with the energetic ion source, collisions, and losses [7-19]. We performed the first numerical demonstration of toroidal Alfvén eigenmodes (TAE) bursts with parameters similar to a TFTR experiment [1] and reproduced many of the experimental characteristics [9]. However, the saturation amplitude of the magnetic field normalized by the toroidal field was higher by one order of magnitude than the value inferred from the experimental plasma displacement measurements. In the simulation of Ref. [9], the only nonlinearity retained was the nonlinearity in the energetic-particle orbits, while the nonlinear MHD effects were neglected. The nonlinear MHD effects on the evolution of a TAE was carefully investigated, and it was found that the energy transfer from the TAE to the nonlinearly generated zonal modes with toroidal mode number $n=0$ and higher harmonics reduces the saturation level of the TAE [20,21].

The multi-phase simulation, which is a combination of classical simulation and hybrid simulation for energetic particles interacting with an MHD fluid, was developed in order to investigate a fast-ion distribution formation process with beam injection, collisions, losses, and transport due to the AEs with the MHD nonlinearity [20-23]. We use the MEGA code [7] for both the classical and hybrid simulations. We run alternately the classical simulation without MHD perturbations and the hybrid simulation with MHD perturbations. The multi-phase simulation is a comprehensive simulation, which deals with both the AEs and the fast-ion transport as self-consistently and realistically as possible, yet attainable on a tractable timescale. It was demonstrated with the
multi-phase simulation of DIII-D discharge #142111 [24,25] that the fast-ion spatial profile is significantly attenuated due to the interaction with the multiple AEs and that the fast-ion pressure profile is in agreement with that of the experiment with the root-mean-square of the deviations same as the error bar [13]. The predicted temperature fluctuation profiles of \( n = 3, 4, \) and \( 5 \) modes were quantitatively compared with ECE measurements, and it was found that the fluctuation profiles as well as phase profiles are in very good agreement with the measurements. Additionally, the saturated amplitudes are within a factor of 2 of those measured. The nonlinear MHD effects [11,20-23] that prevent the AE amplitude from increasing to a large amplitude observed in a reduced simulation [9] are included in the hybrid simulation. The fast-ion profile stiffness that was observed in the DIII-D experiments [26] was also investigated with the multi-phase simulation, and it was demonstrated that the resonance overlap of multiple eigenmodes [27,28] accounts for the profile stiffness with the sudden increase in fast-ion transport with increasing beam power [14]. More recently, the abrupt large-amplitude event observed in the JT-60U experiments has been successfully reproduced with the multi-phase simulation using MEGA code [19]. AE bursts in an LHD plasma were also simulated with the multi-phase simulation, and the AEs observed in the experiment were identified [16].

We performed the multi-phase hybrid simulations for energetic particles and an MHD fluid in order to investigate MHD instabilities driven by fast ions in tokamak plasmas and the fast-ion distribution formed with the instabilities, neutral beam injection, and collisions [15]. The multi-phase simulation was applied to examine the distribution formation process in the collisional slowing-down time scale of fast ions for various beam deposition power (\( P_{\text{NBI}} \)) and slowing-down time (\( \tau_s \)). The physical parameters other than \( P_{\text{NBI}} \) and \( \tau_s \) are similar to those of a TFTR experiment [1]. For \( P_{\text{NBI}} = 10 \text{MW} \) and \( \tau_s = 100 \text{ms} \), which is similar to the TFTR experiment, the TAE bursts take place with a time interval 2ms, which is close to that observed in the experiment. The maximum radial velocity amplitude of the dominant TAE at the bursts in the simulation is \( v_i/v_A = 3 \times 10^3 \). For \( P_{\text{NBI}} = 5 \text{MW} \) and \( \tau_s = 20 \text{ms} \), the amplitude of the dominant TAE is kept at a constant level \( v_i/v_A = 4 \times 10^4 \). It was found that the intermittency of TAE rises with increasing \( P_{\text{NBI}} \) and increasing \( \tau_s \) (=decreasing collision frequency). With increasing volume-averaged classical fast-ion pressure, which is well proportional to \( P_{\text{NBI}} \tau_s \), the fast-ion confinement degrades monotonically due to the transport by the instabilities. The volume-averaged fast-ion pressure depends only on the volume-averaged classical fast-ion pressure, not independently on \( P_{\text{NBI}} \) or \( \tau_s \). Volume-averaged classical fast-ion beta is well proportional to the product of the two parameters \( P_{\text{NBI}} \tau_s \). We found the fast-ion pressure profile resiliency, where the increase in fast-ion pressure profile is saturated, for the cases with the highest \( P_{\text{NBI}} \tau_s \) where the TAE bursts take place.

In the present paper, the time evolution of the fast-ion energy transport flux profile is presented. We have run new simulations with the number of computational particles 16 times larger than that of the previous work [15] in order to investigate the fast-ion distribution function in phase space before and after the AE burst. We clarify the physical process of the AE burst in toroidal plasmas.

2. SIMULATION RESULTS

2.1. Time evolution of fast-ion energy transport flux profile

Figure 1 compares the time evolutions of fast-ion energy transport flux profile between two cases investigated in Ref. [15], case A (\( P_{\text{NBI}}=5 \text{MW} \) and \( \tau_s=20 \text{ms} \)) where the amplitude of the dominant AEs is kept at a constant and low level, and case I (\( P_{\text{NBI}}=10 \text{MW} \) and \( \tau_s=100 \text{ms} \), which are similar to the TFTR experiment) where the AE bursts take place. Four TAEs with toroidal mode numbers \( n=1, 2, 3, \) and \( 4 \) are observed in case A. One energetic particle mode (EPM) with \( n=1 \) and five TAEs with \( n=2, 3, \) and \( 4 \) are observed in case I. At the AE bursts in case I, the growth of all the modes are synchronized. We see in Fig. 1(a) that local transport takes place irregularly with occasional and local radial propagation of transport. In contrast, we see in Fig. 1(b) that the synchronization of multiple AEs generates the global and huge transport flux, which leads to the profile resiliency.
2.2. Fast-ion distribution function in phase space before and after AE burst

We have run two new simulations with the number of computational particles 16 times larger than that of the previous work [15] in order to investigate the fast-ion distribution function in phase space before and after the AE burst. For $P_{\text{NBI}}=10\text{MW}$ and $\tau_s=100\text{ms}$, multiple AEs with toroidal mode numbers $n=1-5$ are destabilized. In this run, the hybrid simulation was performed continuously after $t=25\text{ms}$. The stored fast ion energy is saturated at $t=40\text{ms}$ at about 40% of that in the classical simulation. All the AEs with $n=1-5$ have the synchronized evolution. For the understanding of the synchronized growth, we have analyzed the fast ion distribution function in phase space $f(P_p, E, \mu)$ where $P_p$ is toroidal canonical momentum, $E$ is kinetic energy, and $\mu$ is magnetic moment. Figure 2 shows the fast ion distribution function for counter-going particles in $(P_p, E)$ space for a constant $\mu$ and $t=43.5\text{ms}$ just before an AE burst. We assumed the balanced beam injection, and $\mu$ is chosen for the peak of the beam distribution. We see in Fig. 2 that a stepwise structure is formed in $P_p$ direction, which is roughly the radial direction. The AEs have grown to a low amplitude at $t=43.5\text{ms}$. The stepwise distribution is formed by the local transport due to the low-amplitude AEs.

The fast-ion distribution function just before an AE burst for another run with $P_{\text{NBI}}=5\text{MW}$ and $\tau_s=100\text{ms}$ is compared with that of a classical simulation which started with the data just after the previous AE burst ($t=40\text{ms}$) in the hybrid simulation. The difference between the two distributions is shown in Fig. 3. The red and blue regions correspond to the positive and negative values, respectively. We can confirm in this figure that the stepwise structure is formed after the previous burst for a wide range of energy.
The fast ion pressure profiles averaged in the last 10ms are compared between $P_{\text{NBI}}=5\text{MW}$ and $10\text{MW}$. The central pressure increases only by 15% with the increase of beam power from 5MW to 10MW. We call this saturation of fast ion pressure profile “profile resiliency”. Figure 4 compares the fast ion distributions just before AE bursts between $P_{\text{NBI}}=5\text{MW}$ and $10\text{MW}$. This indicates the profile resiliency not only for fast ion pressure but also for fast ion distribution function. The fast ion distribution during the AE burst is also shown in Fig. 4 for $P_{\text{NBI}}=10\text{MW}$ and $t=44.0\text{ms}$. We see the significant flattening of the distribution.

**FIG. 4.** Comparison of fast ion distribution function just before a burst between $P_{\text{NBI}}=5\text{MW}$ and $10\text{MW}$. The fast ion distribution during the AE burst (black curve) is also shown.

3. SUMMARY

Alfvén eigenmodes (AEs) driven by fast ions in tokamak plasmas and the fast ion distribution formed with the AEs, neutral beam injection (NBI), and collisions are investigated with hybrid simulations for energetic particles and a magnetohydrodynamic (MHD) fluid [15]. The multi-phase simulation [12,13], which is a combination of classical simulation and hybrid simulation, was applied for various beam deposition power ($P_{\text{NBI}}$) and slowing-down time ($\tau_s$). In the classical simulation, energetic particle orbits are followed in the equilibrium magnetic field with neutral beam injection and collisions while the MHD perturbations are turned off. The physical parameters other than $P_{\text{NBI}}$ and $\tau_s$ are similar to those of a TFTR experiment [1]. For $P_{\text{NBI}}=10\text{MW}$ and $\tau_s=100\text{ms}$, which are similar to the TFTR experiment, the AE bursts take place with a time interval 2.7ms and the maximum MHD velocity $v_r/v_A=3\times10^{-3}$, which are close to the TFTR experiment. With increasing volume-averaged classical fast ion pressure, the fast ion confinement degrades monotonically due to the transport by the AEs. The fast ion pressure profile resiliency, where the increase in fast ion pressure profile is saturated, is found for the cases with the AE bursts. In the present work, we have run new simulations with the number of computational particles 16 times larger than that of the previous work [15] and clarified the physical process of the AE burst in toroidal plasmas. Before the AE bursts occur, multiple AEs become unstable, and grow to low
amplitude. The low-amplitude AEs gradually and locally flatten the fast ion distribution in phase space leading to the formation of a stepwise distribution. The stepwise distribution created by the low-amplitude AEs is a “critical distribution” where the further beam injection leads to the higher AE amplitude, the broadening of the locally flattened regions, and their overlap. This resonance overlap of the multiple AEs [27,28] brings about the AE burst, the global transport of fast ions, and the saturation of the distribution.

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