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HYBRID SIMULATION OF ALFVÉN EIGENMODES CAUSED BY MULTIPLE FAST ION SPECIES IN THE LARGE HELICAL DEVICE

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Abstract

Hybrid simulations for multiple fast ion species interacting with a magnetohydrodynamic (MHD) fluid were conducted using the MEGA code to investigate the synergetic effect of multiple fast ion species on the instability and the fast–ion transport in the Large Helical Device (LHD) experiments with the fast protons and fast deuterons. In the MEGA simulations, the Alfvén eigenmode (AE) burst after approaching the steady state of fast-ion stored energy is larger than that before the steady state. Then, there is a significant increase in the fast-ion loss rate. Through comparison with simulations in the case of AEs driven by single fast ion species, the additional AEs are destabilized by multiple fast ion redistributions in the case of multiple fast ions. Consequently, the additional AEs caused increases in the loss rates of both fast protons and fast deuterons. The synergetic effect of multiple fast ions is shown to increase the fast ion transport and loss in the LHD.

1. INTRODUCTION

The fast-ion confinement is a critical issue for the prediction of the heating efficiency in a fusion reactor. The fast-ion confinement depends not only on the collisional transport in the equilibrium magnetic field but also on the fast-ion transport and losses induced by the fast-ion driven instabilities such as Alfvén eigenmodes (AE). Therefore, it is an important challenge to clarify the fast-ion transport due to the fast-ion driven magnetohydrodynamic (MHD) instabilities.

The LHD is one of the largest helical devices with a non-axisymmetric 3-dimensional magnetic configuration. In the LHD, the fast-ion confinement has been investigated by using three tangentially injected neutral beams (NBs). To clarify the relationship between instabilities and fast ion transport in plasma with multiple fast ion species, experiments with the combined injection of hydrogen and deuterium beams were conducted in the LHD. The recurrent AE bursts caused by fast protons and fast deuterons were observed in the experiments [3]. In the plasma with multiple fast ion species, one fast ion species may drive an instability while other species may stabilize it. The stabilizing fast ion species may be transported by the instability driven by other fast ion species. It is important for predicting the confinement of alpha particles to investigate the synergetic effect of multiple ion species on fast-ion transport.

A hybrid simulation code for nonlinear MHD and energetic-particle dynamics, MEGA, has been developed to simulate recurrent bursts of fast-ion driven instabilities, including the source, collisions, and losses [1]. The multi-phase simulation, which is a combination of classical simulation and hybrid simulation, was applied to the LHD experiment #47645[4] in order to investigate the AE burst with beam injection close to the experimental condition [1]. It was found that two groups of AEs with frequencies close to those observed in the experiment are destabilized alternately. The alternate appearance of multiple AEs is similar to the experimental observation [1].

In this work, simulations of LHD experiments with fast protons and fast deuterons were performed using the MEGA code to clarify the instabilities induced by the multiple fast ions and their transport. To identify the synergetic effect of multiple fast ions, the simulation of the LHD experiment was compared with that when AEs were driven by only single fast ions. The synergetic effect of multiple fast ion species on the instabilities and fast ion transport was investigated.

2. HYBRID SIMULATION OF MULTIPLE FAST IONS IN THE LHD

2.1. Simulation condition

A multi-phase simulation of MEGA code was applied to the LHD discharge #155724 [2], in which fast protons were produced by a co-tangentially injected neutral beam (NB), and fast deuterons were generated by co- and counter (ctr)- tangentially injected NB. The word "co" means that the direction of the effective toroidal current is consistent with the clockwise directed rotational transform. The word "counter (ctr)" means the opposite direction. Since the time interval of the AE burst in the LHD experiment is approximately 10 ms, the classical simulation and the hybrid simulation were alternately run for 7 ms and 3 ms, respectively. In the classical simulation, fast-ion orbits were followed with collisions while the MHD perturbations were turned off. The equilibrium magnetic field was calculated by the HINT2 code [5,6] based on the profiles of electron density and temperature measured in the LHD experiment. The magnetic field strength at the magnetic axis was 0.6 T. In this experiment, the injection energy of fast protons and fast deuterons was approximately 180 keV. The port through powers of hydrogen NB and deuterium NB are approximately 4 MW and 3 MW, respectively. Using the density and temperature profiles shown in Fig. 1 (a), the birth positions of fast ions shown in Fig. 1 (b) were calculated by the HFREYA code considering the injection energy of each NB injection.

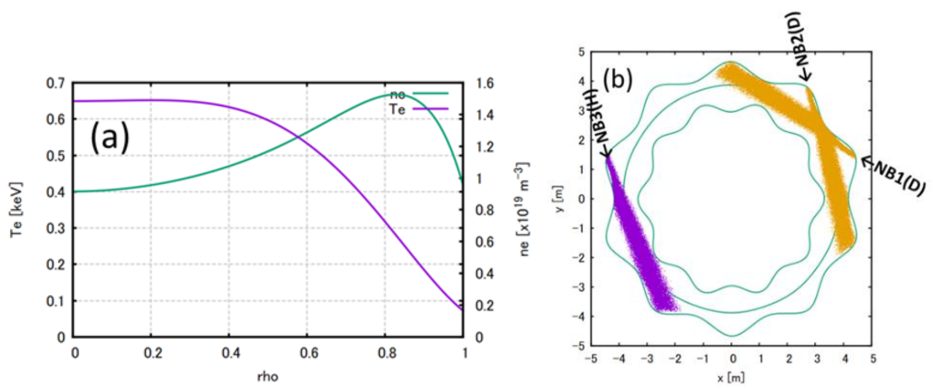

FIG. 1 (a) Electron temperature and density profiles in the LHD discharge #155724 and (b) fast-ion birth locations produced by neutral beam(NB) injection. In panel (a), purple and green lines show the temperature and density profiles, respectively. In panel (b), purple points represent the birth points of the deuteron, and yellow points show the birth points of the protons. These birth points were projected onto the equatorial plane. Green lines represent the last closed flux surface and the magnetic axis.

2.2. Time evolution of AE burst with multiple fast ion species.

In the multi-phase simulation of MEGA, the time evolution of fast-ion stored energy, kinetic MHD energy, and fast-ion loss rate is shown in Fig. 2. In Fig. 2 (a), the AE bursts occur recurrently, and the fast ions are lost during the AE bursts. In particular, the kinetic MHD energy of AE bursts after 57 ms, when the fast-ion stored energy is close to the steady state, is larger than that before 57 ms. And then, the fast-ion loss rate in AE bursts after 57 ms becomes large in all fast-ion species. The most significant component of the fast-ion loss rate is the ctr-injected fast deuteron.

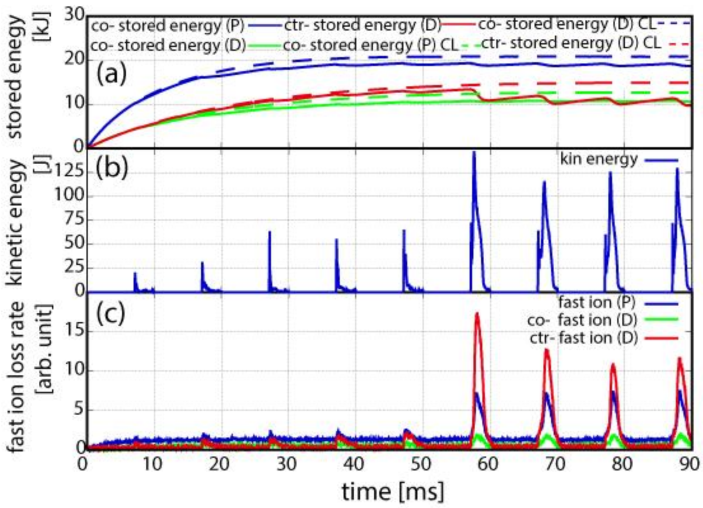

FIG. 2 Time evolution of (a) fast-ion stored energy, (b) kinetic MHD energy, and (c) fast-ion loss rate without prompt loss. In panel (a), the results of the "classical calculation (CL)," are shown together for comparison. "co-" and "ctr-" show fast-ion produced by co-injected NB and ctr-injected NB, respectively. "P" and "D" denote the fast ion species.

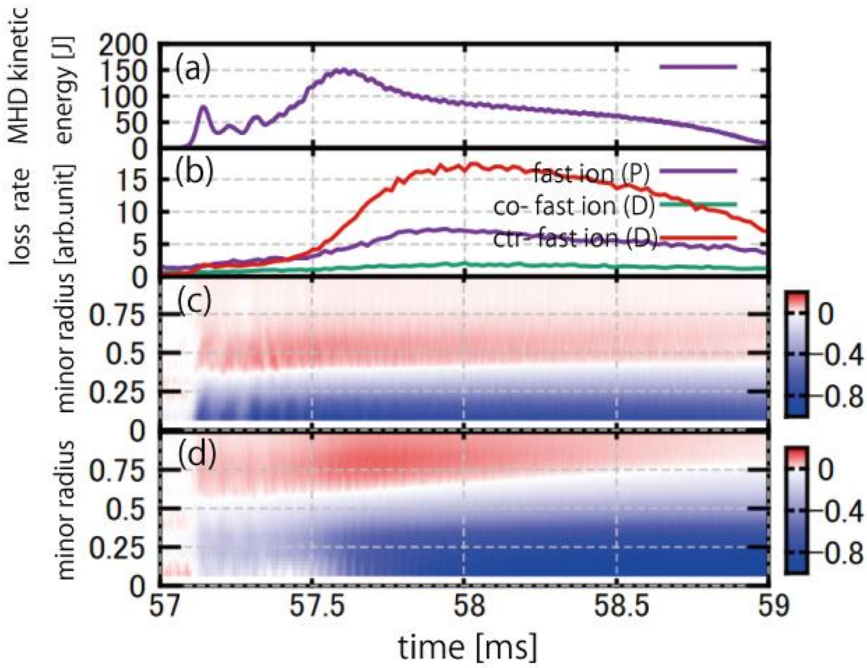

FIG. 3 Time evolutions of (a) kinetic MHD energy, (b) fast-ion loss rate, change of (c) fast proton pressure, and (d) fast deuteron pressure. "P" and "D" denote the fast ion species. In panels (c) and (d), colour represents the difference of fast-ion pressure from that at t=57 ms before the AE burst.

In AE bursts after 57 ms, the synergetic fast-ion transport due to the AE driven by multiple fast ions might have led to an increase in the fast-ion loss rate. Therefore, we investigate the AE burst after 57 ms in detail. Figure 3 shows the time evolution of kinetic MHD energy, fast-ion loss rate, and change of fast-ion pressure from 57 ms. In fig. 3 (a), there are two peaks of kinetic MHD energy in the AE burst. It is seen from Figs. 3 (c) and (d) that the significant changes in fast proton pressure primarily occur near the initial AE peak. And then, in the second AE peak, the fast deuteron pressure decreases in rho <0.5. In particular, fast deuterons with $v_{//} < 0$ are mainly lost in the second AE peak.

We analyze the frequency of AEs in this AE burst (Fig. 4). For reference, the frequencies in cases where AEs are driven by only fast protons and by only fast deuterons are shown in Fig. 4, respectively. In the frequency analysis for AE bursts near 57 ms, AEs in the case of multiple fast ions have primary frequencies of ~60 kHz, ~50 kHz, and ~30 kHz (Fig. 4(a)). The frequencies are consistent with those observed in the LHD experiment [3]. On the other hand, the primary frequencies in cases of only fast protons or only fast deuterons are ~50 kHz (Fig. 4 (b) and (c)). In the case of multiple fast ions, the amplitude of the AE with 60kHz is the largest, and the AEs with 30 kHz are destabilized. These results indicate that the synergistic effects of multiple fast ions induce additional instabilities.

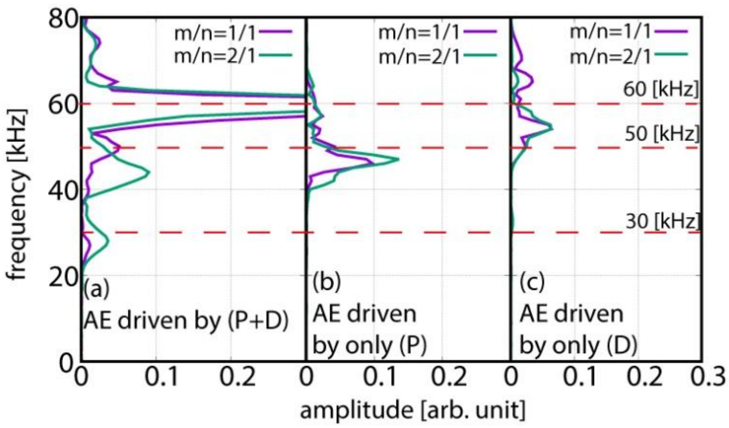

FIG. 4 Frequency spectra of radial MHD velocity harmonics. Panel (a) shows the simulation with fast proton and deuteron. Panels (b) and (c) show the results with the assumption that AEs were driven by only fast protons and only fast deuterons, respectively. In the figures, frequencies of AEs observed in the experiment are indicated by the red dashed lines.

3. SYNERGETIC EFFECT OF MULTIPLE FAST IONS

To clarify the effect of multiple fast ions, the simulation with multiple fast ions is compared with that of AE driven by only a single ion species. Figure 5 (a) shows the time evolution of kinetic MHD energy for AE driven by multiple fast ions and for AE driven only by a single fast ion species. The fast-ion loss rates in the cases of multiple fast ions and AE driven only by fast protons are shown in Fig. 5 (b) and (c), respectively. In the case of AE driven only by fast protons, although AEs are driven only by fast protons, orbits of both fast protons and fast deuterons including the AEs are followed. As a result, changes in the pressure and the energy of both proton and deuteron by the AEs due to only fast protons can be evaluated. In Fig. 5 (a), there is an initial peak of the kinetic MHD energy near 57.1 ms in both the cases of multiple fast ions and AE driven only by fast protons. Note that the kinetic MHD energy in the case of AE driven by only fast deuterons is exceedingly small. Only in the case of multiple fast ions, there is an additional second peak of kinetic MHD energy near 57.5 ms, and then, the fast-ion loss rate becomes large. These results indicate that the redistribution of multiple fast ions due to the initial AE peak induces the second AE peak.

Next, we investigate the synergetic effect for each AE peak in detail. The transferred energy from AE to fast ions and the change of pressure in the initial AE near 57.1 ms (timing A shown in Fig. 5) in the cases of multiple fast ions are compared with that in the case of AE driven only by fast proton. Figure 6 shows the transferred energy from AEs to each fast ion. In Fig. 6, the horizontal axis shows the parallel velocity of fast ions normalized by the Alfvén velocity (v_a) at the magnetic axis. In Fig. 6, the transferred energy of the fast proton in both the case of multiple fast ions and AE driven only by fast proton is negative near $v_{para}/v_a \sim 1.5$. It is found that fast protons with v_{para}/v_a～1.5 induce the AEs in the initial AE peak even in the case of AEs driven by multiple fast ions. In addition, in the case of multiple fast ions, the transferred energy from AEs to the fast deuterons with $v_{para}/v_a < 0$ becomes negative. The fast deuterons with $v_{para}/v_a < 0$ contribute to the destabilization of the initial AE burst. This is one factor why the kinetic MHD energy of the initial AE bursts in the case of AEs driven by multiple fast ions is larger than that in the case of AE driven only by fast protons. Figure 7 shows the fast-ion pressure profiles in the initial AE peaks. It is found from Fig. 7 that the fast proton pressure, which mainly causes the initial AE burst, decreases in rho < 0.3 in the case of AEs driven by multiple fast ions. The change of fast proton pressure in the case of multiple fast ions is almost the same as that in the case of AE driven only by fast protons. Only in the case of AEs driven by multiple fast ions, fast deuteron pressure decreases in rho < 0.4 because of the interaction between AEs and fast deuterons with $v_{para}/v_a < 0$.

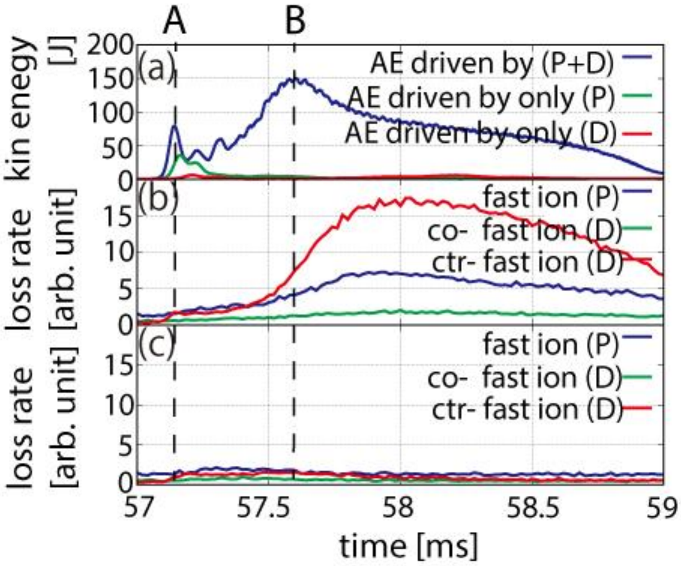

FIG. 5 Comparison of kinetic MHD energy and fast-ion loss rate in the case of AEs driven by multiple fast ions and only a single fast ion species. The panel (a) shows the time evolution of kinetic MHD energy in the case of AEs driven by multiple fast ions and only a single fast ion species. In panel (a), the blue line shows the case of AE driven by multiple fast ions. Green and red lines denote the cases of AE driven by only fast proton and only fast deuteron, respectively. The fast-ion loss rates in the case of multiple fast ions and AE driven only by fast protons are shown in panels (b) and (c), respectively.

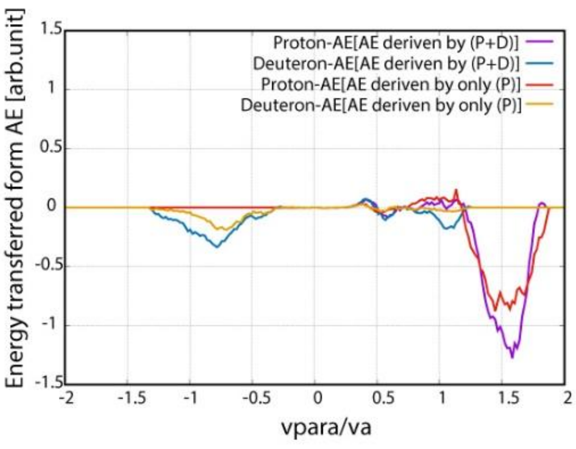

FIG. 6 Transferred energy from AE to fast ions in the case of multiple fast ions and AE driven only by fast protons in the initial AE peak (timing A shown in Fig. 5). In the figure, purple and blue lines show the transferred energy from AEs to fast protons and fast deuterons in the case of AEs driven by multiple fast ions, respectively. The transferred energies from AEs to fast proton and fast deuteron in the case of AEs driven by only fast proton are shown by red and yellow lines. The horizontal axis shows the parallel velocity of fast ions normalized by the Alfvén velocity (va) at the magnetic axis.

We investigate the interaction between the AE and fast ions in the second AE peak, which are destabilized only in the case of multiple fast ions. Figure 8 shows the transferred energy from AEs to fast ions in the second AE peak near 57.6 ms (timing B shown by Fig. 5). In Fig. 8, both fast proton and fast deuteron with vpara/va~0.5 and 0.75 mainly interact with AEs. Note that there is an interaction between AEs and fast ions with vpara/va~0.5 in the initial AE peak (timing A). fast deuterons with vpara/va < 0 were transferred to AEs in the second AE peak (timing B) as well as the initial AE peak (timing A). This interaction between AEs and fast deuterons may be one cause of the increases in losses of ctr- injected fast deuterons.

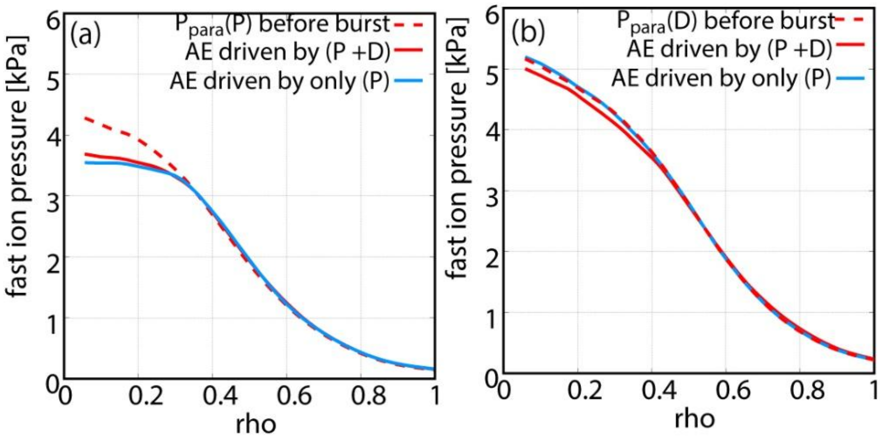

FIG. 7 parallel component of (a) fast proton and (d) fast deuteron profiles in the timing A. In the figures, the red and blue lines represent the fast ion profiles in the cases of AE driven by multiple fast ions and AE driven only by fast protons, respectively. For reference, the fast ion pressure before the AE burst is shown by a dashed line.

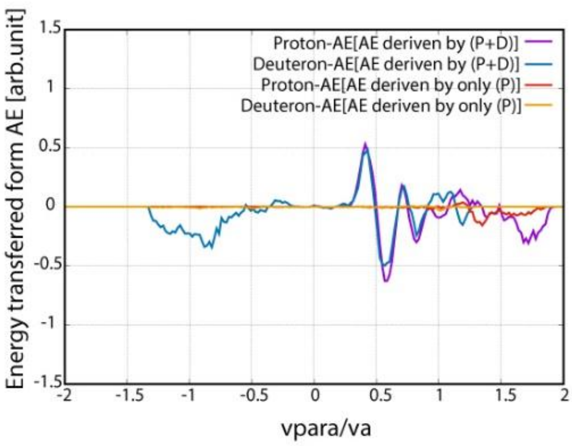

FIG. 8 Transferred energy from AE to fast ions in the cases of multiple fast ions and AE driven only by fast protons at the second AE peak (timing B shown in Fig. 5). In the figure, purple and blue lines show the transferred energy from AEs to fast protons and fast deuterons in the case of AEs driven by multiple fast ions, respectively. For reference, the transferred energies from AEs to fast proton and fast deuteron in the case of AEs driven by only fast proton were shown by red and yellow lines. The horizontal axis shows the parallel velocity of fast ions normalized by the Alfvén velocity (va) at the magnetic axis.

Figure 9 shows the fast ion pressure profiles in the second AE peak (timing B). In the second AE peak, the fast deuteron pressure changes from that at the initial AE peak (timing A). On the other hand, although the fast proton loss rate slightly increases, the fast proton pressure profiles are almost the same as those at the initial AE peak (timing A).

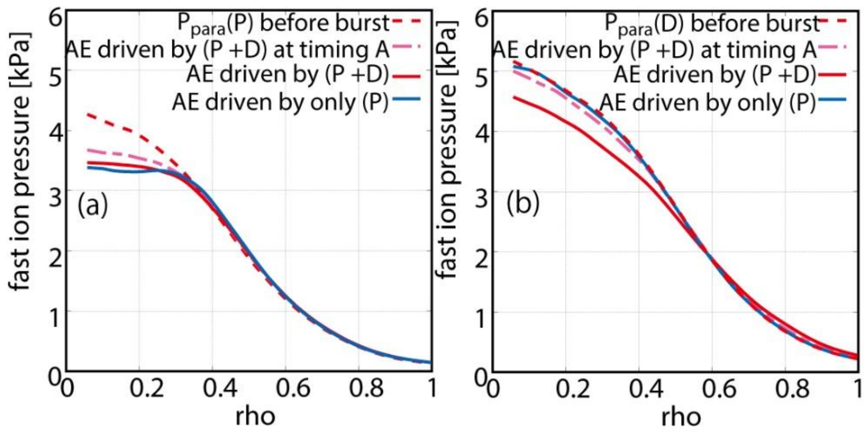

FIG. 9 parallel component of (a) fast proton and (d) fast deuteron profiles in the timing B. In the figures, the red and blue lines represent the fast ion profiles in the cases of AE driven by multiple fast ions and AE driven only by fast protons, respectively. For reference, the fast ion pressure before the AE burst is shown by a dashed line.

4. CONCLUSION

To clarify the instabilities induced by multiple fast ions and their transport, a multi-phase simulation of the MEGA code is applied to the LHD experiments with fast protons and fast deuterons. The synergetic effect of multiple fast ion species on the instabilities and fast ion transport was investigated through the comparison of simulations in the case of AEs driven by single fast ion species.

In the multi-phase simulation of MEGA, in the AE burst after approaching the steady state of fast ion stored energy, a larger AE burst than that before the steady state occurs, and this AE burst causes a significant increase in the fast ion loss rate.

In the AE burst after approaching the steady state of fast-ion stored energy, there are two peaks of kinetic MHD energy. In the initial AE peak, fast protons with $v_{para}/v_a \sim 1.5$ induce the AEs, and the fast proton pressure mainly decreases in rho < 0.3. The fast ion transport due to AEs in the initial AE peak is similar to that in the case of AEs driven only by fast protons. The second AE peak destabilized only in the case of the multiple fast ions, and the second AE peak causes an increase in fast ion loss rate. The results indicate that the additional AEs destabilized due to the multiple fast ion redistribution cause significant fast ion loss. In the second AE peak, both fast protons and fast deuterons with $v_{para}/v_a \sim 0.5$ mainly interact with AEs. The fast deuteron pressure largely changes from that at the initial AE peak.

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