Hybrid simulation of Alfvén eigenmodes caused by multiple fast ion species in the Large Helical Device

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Category and Contribution Type: TH

Hybrid simulations for multiple fast ion species interacting with a magnetohydrodynamic (MHD) fluid were conducted using the MEGA code [1, 2] 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 [3]. In the MEGA simulations, the additional Alfvén eigenmodes (AEs) were destabilized by multiple fast ion redistributions, and the loss rates of both fast proton and fast deuteron significantly increased. The synergetic effect of multiple fast ions was shown to increase the fast ion transport and loss in the LHD.

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 magnetohydrodynamics (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]. In the classical simulation, fast-ion orbits are followed with collisions while the MHD perturbations are turned off. 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 MEGA code to clarify the inabilities induced by multiple fast ion species. The synergetic effect of multiple fast ion species on the instabilities and fast ion transport was investigated. Figure 1 shows the results of the multi-phase simulation of MEGA in the experiment #155724[3]. In this experiment, fast protons with ~ 180 keV are produced by co-injected tangential NB, and, the fast deuterons with ~ 180 keV are injected by co- and ctr- tangential NBs. In Fig. 1, 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. The fast ion loss rate in AE bursts after 57 ms becomes large in all fast ion species. The largest component of the fast ion loss rate is the ctr-injected fast deuteron.

To clarify the effect of multiple fast ions, the simulation with multiple fast ions was compared with that of AE driven by only a single ion species. Figure 2 shows the time evolution of kinetic MHD energy and the change of fast ion pressure. In Fig. 2 (a), there is the peak of the kinetic MHD energy near 57.1 ms in the cases of AE driven by multiple fast ions and AE driven by only fast protons. Note that the kinetic MHD energy in the case of AE driven by only fast deuterons is exceedingly small. In the initial AE peaks, fast proton and deuteron pressure decrease near the plasma center in the case of AE driven by multiple fast ions while there is no change of the fast deuteron pressure in the case of only fast proton (Fig. 2 (b) and (c)). In the case of multiple fast ions, there is an additional peak of kinetic MHD energy near 57.5 ms and the fast ion loss rate becomes large. In the frequency analysis for AE bursts near 57 ms , AEs in the case of multiple fast ions have the primary frequencies of ~60 kHz, ~50 kHz and, ~30 kHz (Fig. 3 (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. 3 (b) and (c)). In the case of single fast ion species, some AEs are missing.

These results indicate that the additional AEs destabilized due to the multiple fast ion redistribution cause large fast ion loss. In the prediction of alpha particle confinement, fast deuteron produced by NBI may play an important role.

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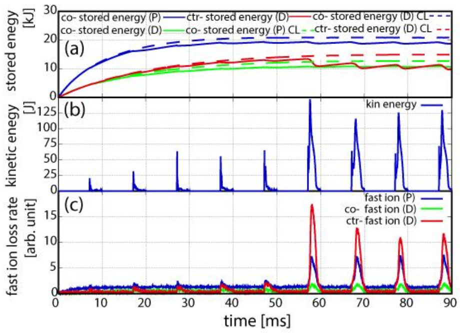

Figure 1 Time evolution of (a) stored fast-ion energy, (b) kinetic MHD energy and (c) fast ion loss rate without prompt loss. In panel (a), the results of the "classical calculation (CL)," are shown together for comparison. "co-" and "ctr- " show fast-ion produced by co-injected NB and ctr-injected NB, respectively. "P" and "D" denote the fast ion species.

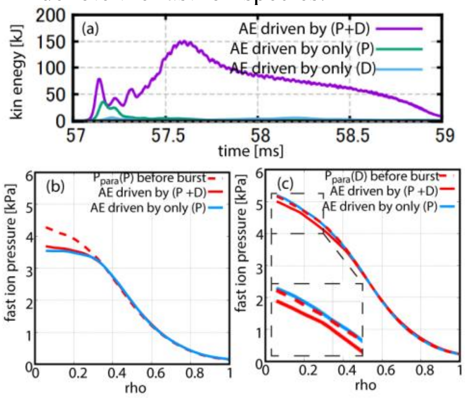

Figure 2 (a) Time evolution of kinetic MHD energy and (b) fast proton pressure and (c) fast deuteron pressure at 57.16 ms. In panel (a), the purple line shows the simulation for with fast proton and deuteron. For reference, green and blue lines show results with the assumption that AEs were driven by only fast protons and deuterons, respectively. In panels (b) and (c), dashed lines show the fast ion pressure profiles before the AE burst.

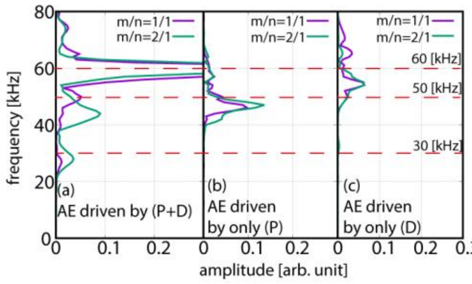

Figure 3 Frequency spectra of radial MHD velocity harmonics. Panel (a) shows the simulation with fast proton and deuteron. Panels (b) and (c) show the results with the assumption that AEs were driven by only fast protons and only fast deuterons, respectively. In the figures, frequencies of AEs observed in the experiment are indicated by the red dashed lines.