INVESTIGATION OF DOUBLE FREQUENCY FISHBONE IN EAST WITH NEUTRAL BEAM INJECTION

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1. INTRODUCTION AND EXPERIMENTAL OBSERVATIONS

In burning plasmas, energetic particle physics is a key issue. Instabilities excited by energetic particles such as fishbones, could induce energetic particle transport and degrade energetic particle confinement. In addition, hybrid scenario with very flat safety factor q around unity in the core region has been recommended for high performance operations in tokamaks. In such scenarios, high-order harmonics with mode number m=n can be excited. In this work, the global hybrid code M3D-K [1, 2] is applied to analyse the fishbones with mode numbers m/n=1/1 and 2/2 observed in EAST with neutral beam injection (NBI).

Fig. 1 illustrates that as the plasma density is progressively reduced in EAST, two distinct varieties of sawtooth crashes become evident from the core SXR signals. The first variety of sawtooth collapse is marked by a relatively minor amplitude and is accompanied by a fishbone mode driven by fast ions. The presence of a fishbone mode with an m/n=2/2 mode amplitude that rivals the fundamental m/n=1/1 mode. In contrast, the second type of sawtooth event is characterized by a more significant collapse amplitude and is associated with an m/n=1/1 fishbone mode, but without a discernible m/n=2/2 fishbone mode. Intriguingly, high-frequency BAEs in the range of f~ [60 80] kHz emerge prior to the sawtooth collapse.

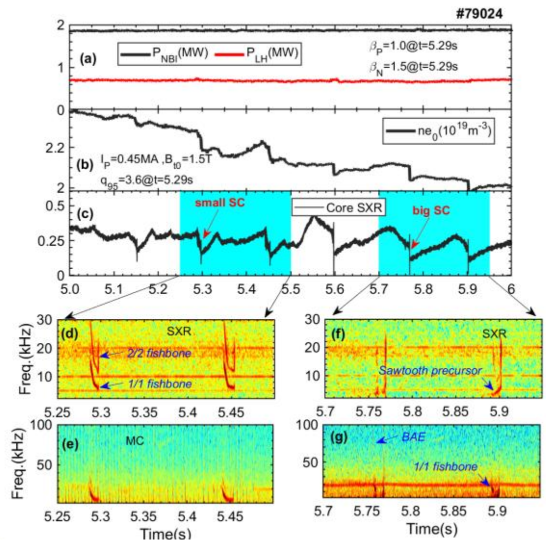

FIG. 1. Observation of m/n=2/2 fishbone and BAE in EAST NBI discharge with a low plasma density.

2. SIMULATION RESULTS AND ANALYSIS

Nonlinear simulations of the fishbone with toroidal mode numbers from n=0 to n=2 show that the n=2 fishbone grows and is force-driven by the n=1 fishbone as the growth rates of the n=2 and n=1 fishbones are $\gamma_{n=2} \approx 2\gamma_{n=1}$. The simulated mode structures and frequencies of both the m/n=1/1 and m/n=2/2 fishbones are consistent with EAST experimental measurements, and the comparisons of n=1 and n=2 fishbone mode structures between simulation and experiment are shown in Figs. 2 (c) and (d). In addition, it is found that n=0 zonal component coupled with both *n*=1 and *n*=2 fishbones saturates at higher level compared to that just coupled with *n*=1 fishbone, which indicates that the nonlinear excitation of *n*=2 fishbone can result in higher zonal flow saturation level, and may be beneficial to suppress turbulence and improve plasma confinement in the core region.

Mode frequency evolutions of the *m*/*n*=1/1 and *m*/*n*=2/2 fishbones are shown in Figs. 2 (a) and (b). It is found that the frequency of the *m*/*n*=2/2 fishbone is around twice of the *m*/*n*=1/1 fishbone, and they chirp down together. At later nonlinear phase, the frequency of the *m*/*n*=2/2 fishbone chirps up and it transits to a high frequency BAE. Moreover, the chirping up phenomenon of the *m*/*n*=2/2 fishbone at later nonlinear phase is similar with experimental observation.

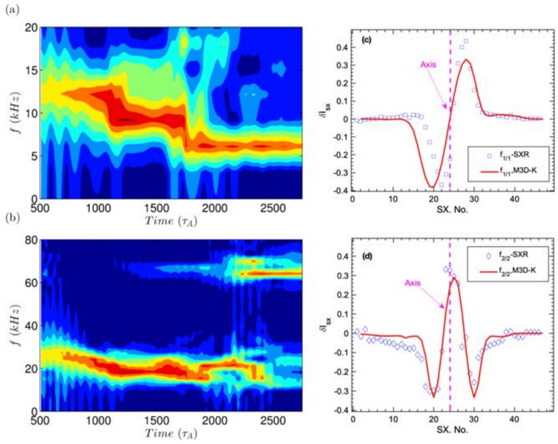

FIG. 2. (a) m/n=1/1 fishbone frequency, (b) m/n=2/2 fishbone frequency, (c) m/n=1/1 fishbone structure, (d) m/n=2/2 fishbone structure.

Time evolution of beam ion distribution in phase space is shown in Fig. 3. During the linear phase shown in Fig. 3 (a), the large d*f*/*f*₀ structure is consistent with the resonant conditions $\omega_\phi = 0.025\,\omega_A$ for the *m*/*n*=1/1 fishbone and $2\omega_\phi = 0.050\,\omega_A$ for the *m*/*n*=2/2 fishbone. During the early nonlinear phase shown in Fig. 3 (b), the frequency of the *m*/*n*=2/2 fishbone chirps down together with the *m*/*n*=1/1 fishbone. During the later nonlinear phase shown in Fig. 3 (c) when the BAE is excited, the corresponding resonant line $2\omega_\phi + 2\omega_\theta - 0.138\omega_A = 0$ is located in the redistribution region of beam ions, which shows the excitation of BAE is related to beam ion transport in phase space. Moreover, in comparison of the *m*/*n*=2/2 fishbone with and without MHD nonlinearity, it is found that the saturated level and transition to high frequency BAE are similar, which means that the energetic particle nonlinearity is dominant for the *m*/*n*=2/2 fishbone saturation and transition to BAE.

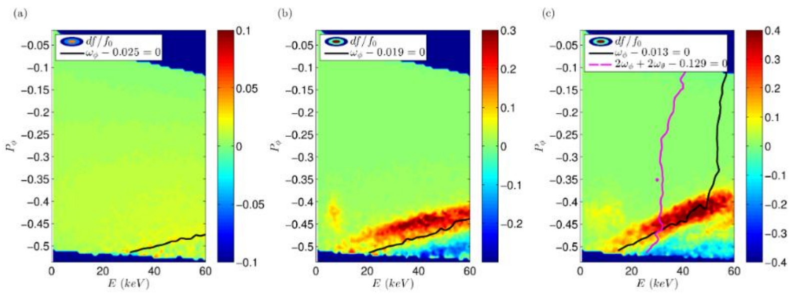

FIG. 3. Distribution change of fast ions df compared to initial fast ion distribution f_0 in phase space with $\Lambda \equiv \mu B_0/E = 1.0$ at different time. (a) $t = 750\,\tau_A$, (b) $t = 1500\,\tau_A$, (c) $t = 2900\,\tau_A$.

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