Effect of Ion Cyclotron Acceleration on Frequency Chirping Beam-Driven Instabilities in NSTX

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The fast-ion distribution function in the National Spherical Torus Experiment (NSTX) is modified from shot to shot while keeping the total injected power at ~2 MW. Deuterium beams of different energy and tangency radius are injected into helium L-mode plasmas, producing a rich set of instabilities, including TAE modes, 50-100~kHz instabilities with rapid frequency sweeps or chirps, and strong, low frequency (10-20 kHz) fishbones. The experiment was motivated by a theory that attributes frequency chirping to the formation of holes and clumps in phase space. In the theory, increasing the effective collision frequency of the fast ions that drive the instability can suppress frequency chirping. In the experiment, high-power (~3 MW) harmonic fast wave (HHFW) heating accelerates the fast ions in an attempt to alter the effective collision frequency. Steady-frequency TAE modes excited early in the discharge are affected by the HHFW heating but there is no evidence that the chirping of 20-100 kHz modes is suppressed.

An understanding of the nonlinear dynamics of fast-ion instabilities is essential to predict the amplitude and subsequent fast-ion transport associated with alpha-driven instabilities in ITER and other burning plasmas. Some instabilities, such as the classic fishbone, have frequencies that change by a factor of two on a millisecond timescale while other instabilities, such as the TAE, have frequencies that are virtually constant on this timescale. In this paper, frequency ``chirping'' refers to large changes in frequency on a sub-millisecond timescale.

The phenomenon of rapid chirping driven by energetic particles is extremely common. The widespread nature of the phenomenon in systems with different instabilities and different energetic particle populations suggests that a generic theoretical model of the coupled wave-particle system might describe the essential features. Berk, Breizman, and collaborators have attempted to develop such a model. They explore a simplified system: the classic ``bump-on-tail'' Bernstein-Greene-Kruskal (BGK) problem of a distribution function that excites electrostatic waves. The basic idea is that the velocity-space gradient that drives the instability is analogous to the configuration-space gradient that drives fast-ion instabilities. Flattening of the distribution function in velocity space corresponds to fast-ion transport. Berk *et al.* find that several frequencies determine the nonlinear dynamics of such a system [1]. The response depends on the characteristic bounce frequency of the resonant particle trapped in the finite amplitude wave ω_B. The rate ν_{eff} that particles leave and enter the resonance region in phase space due to collisions (or other relaxation processes) affects the evolution of the system. The linear growth rate γ_L of the kinetic drive and the damping of the background plasma γ_d are also important. In their model [2], frequency chirping is associated with the formation of holes and clumps in the phase space that describes the fast-particle distribution function. When collisions are weak, these phase-space structures persist and frequency chirping is possible. When the effective collision rate is large, the structures are rapidly destroyed and no frequency chirping occurs.

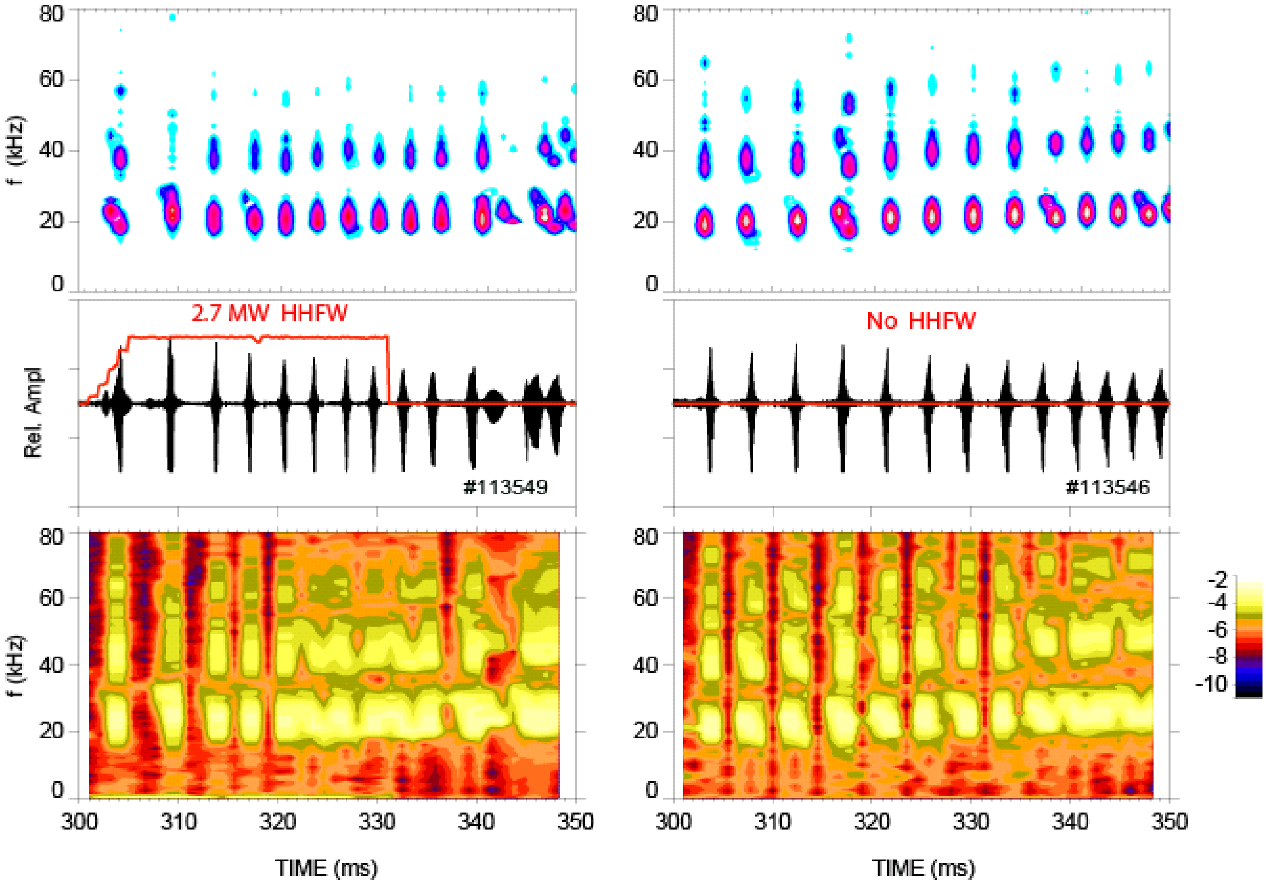

Figure 1. Magnetics spectra, raw signal, and cross power during fishbone activity for discharges with and without HHFW heating.

Recently, a detailed test of the Berk-Breizman model was performed in a dipole experiment [3]. A population of energetic electrons drove a strongly chirping interchange instablity. When electron cyclotron heating was added to increase the effective collision frequency of the resonant electrons, chirping was suppressed. Quantitative estimates of γ_L, γ_d, ω_b, and ν_{eff} explained the observations. The experiment reported here was motivated by this dipole experiment. The basic idea of the experiment was to use neutral beam injection to create chirping instabilities, then use high harmonic fast wave (HHFW) heating to increase ν_{eff} of the resonant fast ions, thereby suppressing the frequency chirping.

The results of the experiment were unexpected: HHFW had no effect on the strongest chirping instabilities. Figure 1 shows a pair of nominally identical discharges with strong fishbone instabilities. The HHFW has no detectable impact on the modes. Similarly, application of HHFW earlier in the discharge, when rapidly chirping modes in the TAE band occurred, also had no effect (Fig. 2). In contrast, application of HHFW did suppress TAE modes with steady frequencies. Also, chirping of ~ MHz GAE modes was altered by HHFW heating.

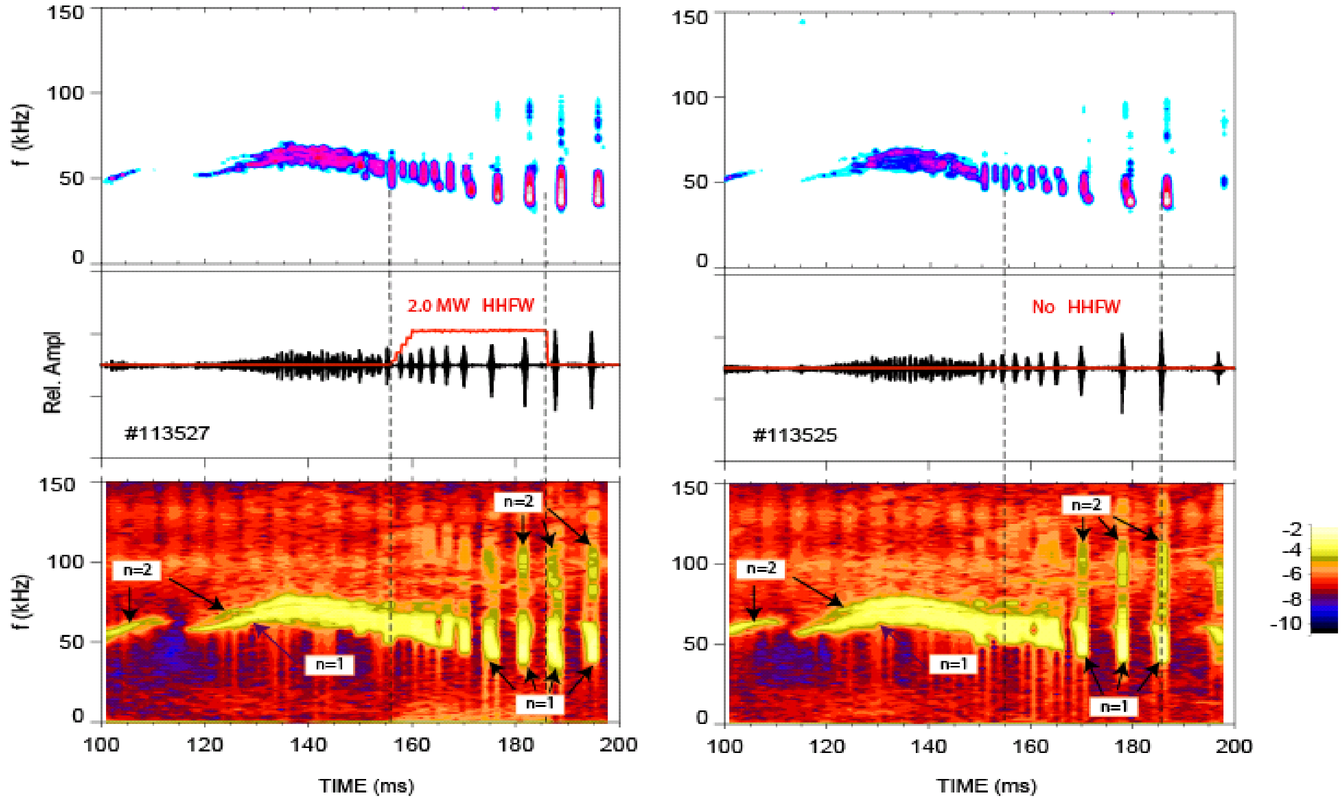

Figure 2. Magnetics spectra, raw signal, and cross power during chirping activity in the TAE band for discharges with and without HHFW heating. The toroidal mode numbers are indicated.

Neutral particle measurements show that fast ions were accelerated by the HHFW heating. Calculations suggest that the ion cyclotron waves interacted with fast ions throughout the plasma and in most of velocity space, so it is likely that the ions that resonate with the fast-ion driven instability were accelerated. Estimates indicate that the increase in ν_{eff} was more than adequate to suppress chirping if the Berk-Breizman model was applicable.

Recent calculations by Vann [4] suggest that strongly driven (called “non-perturbative” because the fast ions alter the mode structure) instabilities exhibit different frequency chirping behavior than the “perturbative” instability studied by Berk *et al*. A likely hypothesis is that the HHFW heating failed to suppress chirping of the ~20 kHz and ~50 kHz instabilities because these modes are Energetic Particle Modes [5]. In contrast, the interchange mode studied in Ref. [3] is a normal mode of the background plasma.

A full-length paper on this study will be submitted in late 2005 to the Physics of Plasmas.

References

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