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Observation of Hole-Clump Pair Generation by Global or Compressional Alfvén Eigenmodes

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Introduction

Neutral beam injection on NSTX excites a broad spectrum of modes in the frequency range $0.2\ \omega_{ci} \leq \omega \leq \omega_{ci}$, believed to be Global and/or Compressional Alfvén eigenmodes (GAE/CAE). These modes are excited through resonant interactions with the beam ions, which may be moving several times faster than the local Alfvén speed. These modes (CAE/GAE) are natural resonances of the plasma, with well-defined frequencies determined by global plasma parameters. However, the modes are often observed to have a bursting character where the frequency changes during each burst by as much as 30% on millisecond timescales; the modes "chirp". In this paper we will exam this behavior in the context of the "hole-clump" theory of chirping modes [1].

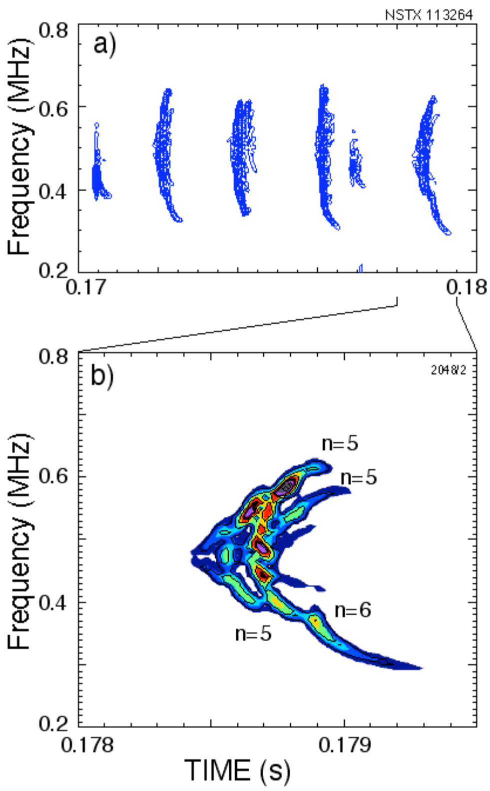

Fig. 1. Spectrogram of Mirnov coil showing multiple chirping bursts in upper panel and an expanded view in lower panel with toroidal mode numbers indicated.

Experimental Results

In Figure 1a is shown a spectrogram of Mirnov coil data over the frequency range from 0.2 MHz to 0.8 MHz. There are six fluctuation bursts in this time window where the frequency chirping spans ≈ 300 kHz. The plasma is heated with 4.7 MW from three neutral beam sources at energies of 70 keV, 74 keV and 92 keV. The plasma current is being ramped and increases from 0.77 MA to 0.85 MA during this time. The plasma is in H-mode, with central density increasing from ≈ 2.3 x $10^{19}/m^3$ to ≈ 2.6 x $10^{19}/m^3$. The toroidal field is ≈ 2.6 kG.

A single burst is further expanded in Fig. 1b. In this example the mode chirps both up and down over a frequency range of about 150 kHz, or $\delta f/f_0 \approx 30\%$. The entire chirp event in Fig. 1b lasts about 0.9 ms. "Inside" the main mode peaks, are a set of secondary modes, either independent modes, or the satellite modes seen in hole-clump simulations [1], possibly excited by the changes in the fast ion distribution resulting from this event. The downward chirping component lasts longer, but has lower amplitude than the upward chirping component. The down and upward chirps appear to consist of a sequence of discrete modes. More commonly, bursts are seen where only the downward (or more rarely, upward) chirp is seen.

The modes propagate in the toroidal direction counter to the plasma current and neutral beams, *i.e.,* the ω_{*e} direction. The toroidal mode numbers for both the upwards and downwards chirps, and for most of the secondary modes are measured to be n = 5. The lowest frequency and last of the secondary modes has n = 6. The polarization of the mode (shear vs. compressional) as measured at the vacuum vessel wall suggests the mode has mixed polarization, and is not inconsistent with expectations for either the Global Alfvén Eigenmode (GAE) or the CAE in complex geometry. No information on the poloidal structure is presently available.

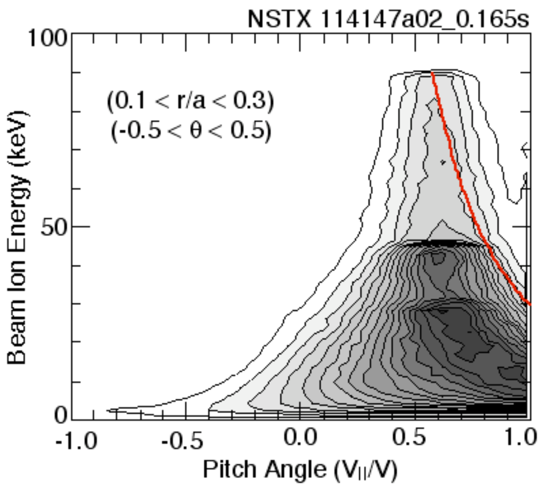

Fig. 2 Fast ion distribution function calculated by TRANSP. Red line indicates fast ion resonant with mode.

ANALYSIS

The CAE and GAE are believed to be excited through a Doppler-shifted ion-cyclotron resonance [2] with the resonance condition $\omega = \omega_{ci} - k_{\parallel}V_{b\parallel}$. The parallel wave number, $k_{//}$, is not measured. Assuming, for example, that the modes are GAE, the local dispersion relation for the GAE, $\omega_{GAE} = k_{//}V_{Alfvén}$, also constrains the parallel wave number. The resonance condition may then be written as $V_{b//}/V_{Alfvén} = (\omega_{ci} - \omega)/\omega$. For the example shown in Ref. 3, Fig. 13, the mode frequency was 0.46 MHz Doppler shifted to 0.39 MHz, the ion cyclotron frequency was 1.67 MHz and $V_{b}/V_{Alfvén} \approx 4.7$, so full-energy (90 keV) beam ions with a pitch angle $V_{b//}/V_b \approx 0.57$ will match the resonance condition. This rough estimate is a good match to the pitch angle of the perpendicular bump-on-tail in the fast ion distribution calculated by TRANSP shown in Fig. 2.

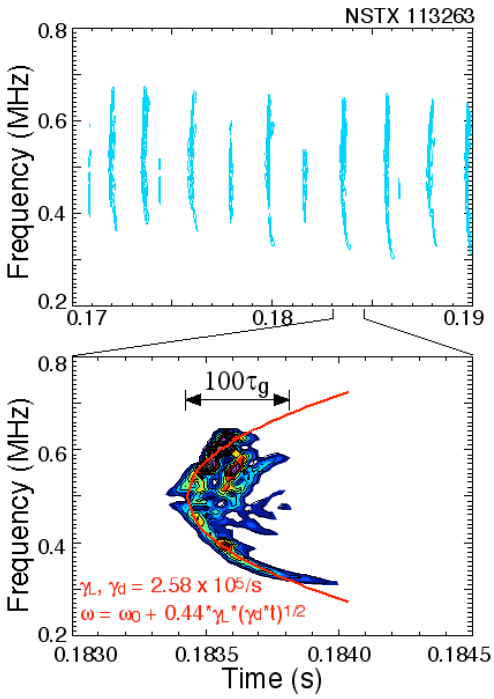

Fig. 3. Spectrogram of Mirnov coil data in top panel showing multiple chirping bursts. Lower panel expands a single burst. Red curve shows fit to Hole-Clump theory.

The theory proposed by Berk, Briezman and Petviashvili [1] for spontaneous generation of hole-clump pairs predicts that the non-linear interaction of marginally unstable resonant modes with a collisionless, inverted fast-particle distribution results in the splitting of the mode frequency (upward and downward frequency chirping) as "holes" and "clumps" formed in the distribution function propagate in particle phase space. The theory predicts (for $\delta\omega/\omega_0 << 1$) that the frequency chirps follow the simple expression $\omega = \omega_0 \pm 0.44\gamma_L(\gamma_D t)^{1/2}$. Furthermore, the theory predicts the formation of hole-clump pairs only for modes close to the marginal point, so for simplicity in Figure 3 it was assumed that $\gamma_L \approx \gamma_D$, reducing the expression to a single parameter fit. The fit then gives an estimate of the order of magnitude of the drive and damping rates.

STABILIZATION WITH HHFW HEATING

The persistence of the burst and frequency chirp depends on the effective collisionality in the fast ion distribution near the holes and clumps [1]. Increasing the effective collisionality can shorten the period of the bursts. It has been demonstrated that heating of the fast ion distribution, e.g., by radiofrequency waves, increases the effective fast ion diffusivity, which tends to wash out the phase space structures, suppressing the chirping behavior [4].

High harmonic fast wave heating (HHFW) has been seen to heat the fast beam ions on NSTX [5]. In some cases where HHFW was combined with the neutral beam injection heating, suppression of the GAE/CAE chirping modes was observed. In Fig. 4 is shown the rms fluctuation level between 0.5 and 1.5 MHz. Bursts appear shortly after NBI heating, but they change character and disappear with HHFW heating. In the pictograms in the top row of Fig. 4 (boxes not to scale), typical hole-clump Angelfish are seen before HHFW. During HHFW the frequency chirps have reduced range and the bursts have shorter duration. However, occasional large bursts, similar to pre-HHFW bursts are seen. However, in the post HHFW period, the modes no longer chirp, and the "bursting" character is the result of sawteeth. It may be that the GAE/CAE are stabilized with RF through a gross modification of the fast ion distribution. A similar discharge, but without HHFW showed Angelfish bursts throughout. More experimental work is required to document HHFW power thresholds for stabilization, and the importance of the HHFW antenna phasing.

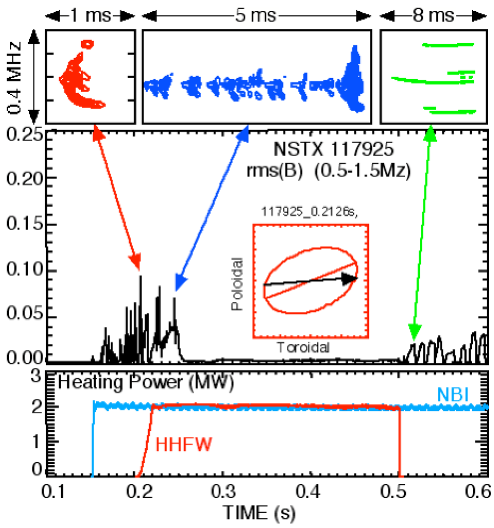

Fig. 4 Stabilization of chirping modes with High-Harmonic Fast Wave heating. Top row show pictograms of select bursts. Middle panel shows rms fluctuation (black) and inset shows polarization of 0.77 MHz burst (red). Bottom panel shows heating profiles.

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