Observation of Compressional Alfvén Modes During Neutral-Beam Heating on the National Spherical Torus Experiment

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Neutral-beam-driven compressional Alfvén eigenmodes at frequencies below the ion cyclotron frequency have been observed and identified for the first time in the National Spherical Torus Experiment. The modes are observed as a broad spectrum of nearly equally spaced peaks in the frequency range from $\approx 0.2\omega_{ci}$ to $\approx 1.2\omega_{ci}$. The frequency has a scaling with toroidal field and plasma density consistent with Alfvén waves. The modes have been observed with high bandwidth magnetic pickup coils and with a reflectometer.

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Interactions of fast ion tails with magnetohydrodynamic (MHD) instabilities has long been of interest in the magnetic fusion energy (MFE) community. Wave particle interactions can be harmful in that they can induce the loss of energetic ions [1,2] or beneficial in that they "channel" energy from the fast ion population to the thermal ion population [3] (rather than the thermal electrons). Many present experiments rely on fast ions created by radio frequency waves or from neutral beam injection (NBI) to heat the plasma. Proposed MFE fusion reactors will rely on energetic fusion alpha particles to keep the plasma at temperatures high enough to maintain thermonuclear fusion. Understanding the role played by fast ion-wave interactions in these experiments is crucial to improving the prospects for a fusion reactor.

The National Spherical Torus Experiment (NSTX) is a low aspect ratio ($R_{\mathrm{major}}/r_{\mathrm{minor}} \approx 0.85$ m/0.65 m) toroidal device [4]. The range of operational parameters used for the experiments discussed here is 0.7–1.0 MA of toroidal plasma current, 3.0–4.5 kG toroidal field, central electron density of $1-5 \times 10^{19}/\mathrm{m}^3$, and central electron temperature of up to ≈ 1 keV. The plasmas were heated with 1.5–3 MW of deuterium NBI power at a full energy of 80 kV.

The neutral-beam injection energy translates to a beam ion velocity 2–4 times the Alfvén speed and thus Alfvénic waves are likely to be excited. The beam velocity is $V_b \approx 2.8 \times 10^6$ m/s. The Alfvén velocity is $V_A \approx 0.9 \times 10^6$ m/s at an electron density of 3×10^{19} m^3 and a magnetic field of 3 kG (for a nominal deuterium plasma). This ratio is similar to the ratio of the velocity of fusion α's to V_A in an ST reactor. There is a large population of fast ions available to drive the wave; the calculated volume averaged beam beta is of order 20% of the total plasma beta. The NBI geometry and relatively large orbit size of the beam ions result in an anisotropic pitch angle distribution for the fast ions. This anisotropy can provide the energy source to drive instabilities. Similar anisotropies are invoked to drive waves in the earth's magnetosphere [5,6]. The instabilities driven are those where the fast ions transfer more energy to the wave than is lost through damping terms (e.g., electron and ion Landau damping on the thermal population).

The sheared magnetic field geometry, resulting from a peaked toroidal plasma current density profile, together with the nonuniform magnetic field on a flux surface from toroidal geometry and elongation couple Alfvén waves of different poloidal mode numbers. This opens a continuum gap and weakly damped discrete toroidal Alfvén eigenmodes (TAE) exist inside the frequency gap [7,8]. Alternatively, it was shown that, in cylindrical geometry, the spatial variation of the Alfvén velocity can provide the effect of a "potential well" for compressional Alfvén eigenmodes (CAE) [9]. This cylindrical model has since been extended to toroidal geometry [10] and then low aspect ratio geometry [11]. For the CAE the effective $k_{\parallel}$ remains small, the electron and ion Landau damping is weak, and the drive from fast ions can destabilize the mode. A similar model was previously invoked to explain the observation of ion cyclotron emission from tokamak plasmas [12].

With the first injection of neutral beams on NSTX, a broad and complicated spectrum of coherent modes was seen between ≈ 400 kHz and (up to) 2.5 MHz (where ω_{ci} for deuterium is ≈ 2.2 MHz) and less often in the 50–150 kHz range (Fig. 1). The higher frequency modes have been identified as magnetosonic waves or CAE excited by a cyclotron resonance with the neutral-beam ions. The lower frequency modes are thought to be related to the TAE modes seen commonly in tokamaks with energetic fast ion populations resulting from ion-cyclotron range of frequency heating and NBI heating. There is no clear indication of enhanced fast ion losses associated with the modes.

The principal diagnostics for detecting the mode are the fast Mirnov coil array and the UCLA reflectometer [13]. The Mirnov coil design has an intrinsic bandwidth

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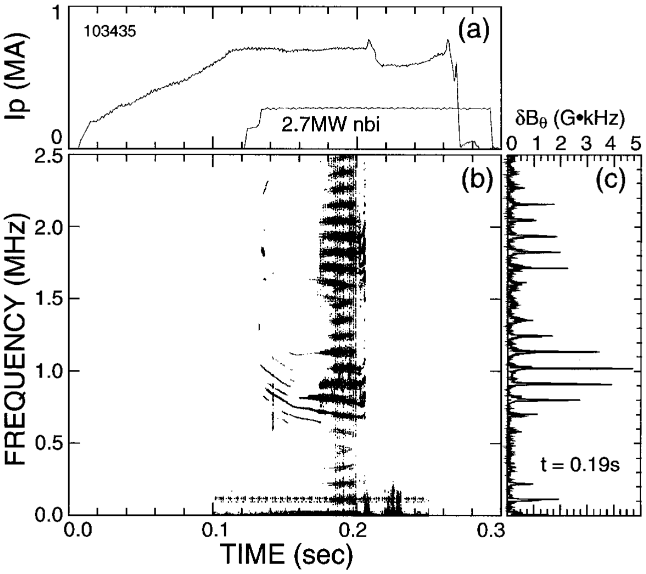

FIG. 1. (a) Traces show evolution of the plasma current and neutral-beam heating. (b) Spectrogram of magnetic fluctuations. (c) Fluctuation spectrum at 0.19 s.

of >3 MHz. The coils are mounted on the vacuum vessel walls, approximately 20 cm outside the plasma. At present there is only a limited amount of experimental data available for studying the poloidal and toroidal structures of the modes.

The data shown in Fig. 1 illustrate several common features of these modes. The modes begin at about 10–50 ms after the start of neutral-beam injection. The mode frequencies drop with time and, in this example, the mode activity is terminated by the onset of a lower frequency MHD instability which results in a major reconnection of the magnetic flux. Figure 1 shows that the mode frequencies are approximately evenly spaced up to at least 2.5 MHz (the bandwidth of the system). The mode spacing in this example is nearly uniform at about 130 kHz and the peaks appear in two bands spanning 400–1500 kHz and 1500–2500 kHz. The bands are not only apparent in amplitude, but also subtle variations in the spacing of the frequency peaks suggest that these are distinct bands, e.g., the frequency gap at 1.53 MHz is slightly wider, even though the spacing of the gaps in each of the bands is very similar. Figure 2 shows a higher resolution spectrum of the same data from slightly later in time. Each of the peaks now has satellite peaks shifted by ≈25 kHz. Detailed measurements of the mode localization have not yet been done. However, the initial data from the reflectometer shows that the mode does drive density fluctuations in the plasma (Fig. 3). The reflectometer measures the displacement of constant density contours. While there is qualitative similarity in the spectra, there is not a direct correlation of spectral peaks between the magnetic fluctuation data and the reflectometer data, possibly as a result of the internal versus edge locations of the measurements, the different parameters being measured, or the fast time dependence of the spectrum.

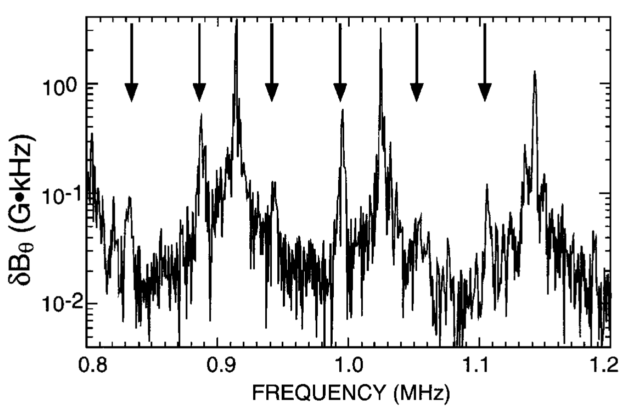

FIG. 2. Higher resolution spectrum of the data shown in Fig. 1 at 0.197 s showing finer splitting of the peaks.

Scaling of the mode frequency with toroidal field and density was studied by ramping the toroidal field up and down in similar shots and by the natural density evolution in each plasma discharge. Figure 4 shows spectra from two similar plasmas, the first in which the toroidal field was ramped upward and the second in which the toroidal field was ramped downward (in both cases the ramps began at 0.13 s). The evolution in the density was similar for these two shots. The dependence of the mode frequency on the magnetic field is found by tracking a large mode in each plasma, starting at the same frequency (≈1.3 MHz) prior to the field ramp. The magnetic field evolution is calculated in the plasma analysis code TRANSP, and the time dependence of $\mathrm{mod}(B)/n^{1/2}$ at a major radius of 1 m is overlaid as the dashed line. The difference in $\mathrm{mod}(B)$ between the two shots at 0.2 s was

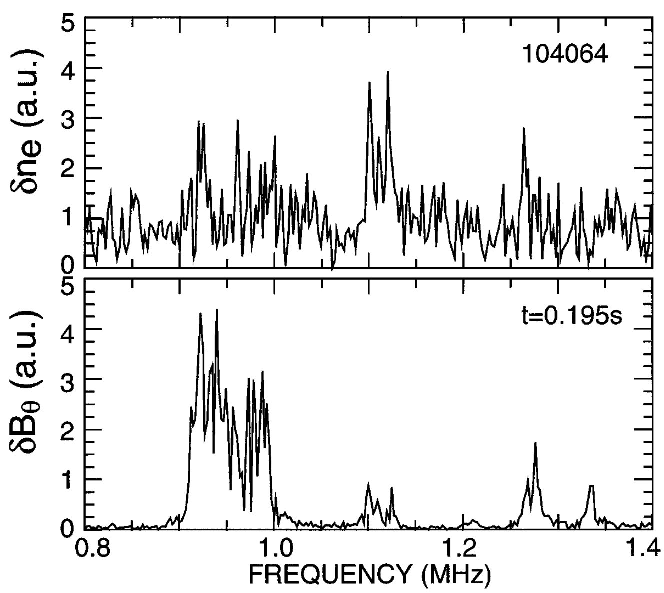

FIG. 3. Spectra of density fluctuations as measured with the reflectometer and compared to magnetic fluctuation spectra at the same time.

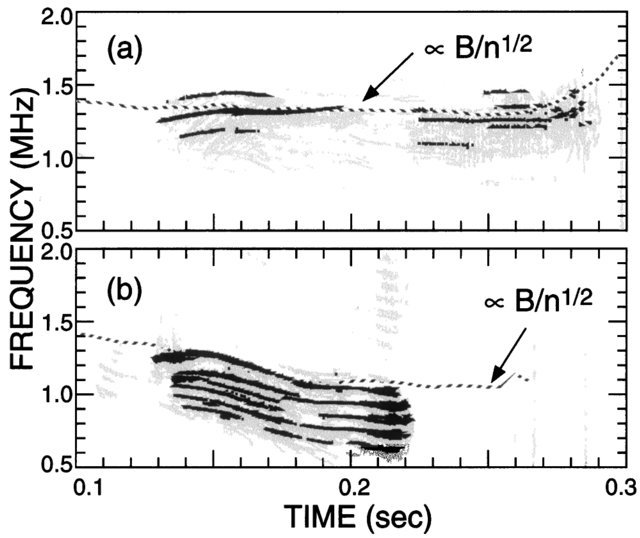

FIG. 4. Magnetic fluctuation spectra from two nearly similar shots, (a) with an upward ramp in toroidal field and (b) with a downward ramp (shot Nos. 103932,103936).

about 27% and the difference in mode frequency was about 25%. In these early NSTX plasmas, the density increases nearly linearly during the neutral-beam injection period and it is not possible to perform similar comparison experiments as was done for the toroidal field scan. The downward evolution of frequency during NBI is, however, roughly consistent with the square root density dependence. From these experiments it was found that the mode frequency showed Alfvénic dependence, being proportional to the magnetic field strength and inversely as roughly the square root of the density.

The mode behavior varies between quasisaturated modes with nearly constant amplitude and a bursting behavior reminiscent of the fishbone instability [1]. All of the modes have the same time behavior. The period between bursts is ≈ 2 ms and the duration of a burst is ≈ 0.1–0.2 ms. Figure 5 shows the magnetic fluctuation signal on a short time scale. During the bursts, the growth rate for the envelope of modes is approximately 10^4 s, or 0.1% of the mode frequency, and the damping rate is comparable or slightly faster.

The stability of modes is determined by the fast ion population, but the mode frequency appears to be a property of the background plasma, i.e., the modes are not fast ion or energetic particle modes. Figure 6 shows a spectrogram of magnetic fluctuations where the NBI injection angle, thus a fast ion pitch angle, has been changed at 0.22 s. As can be seen, some modes persist through the change, indicating that the mode frequency is a background plasma parameter. Other modes are stabilized, indicating that the new fast ion distribution does not couple to them.

The modes have been identified as compressional Alfvén eigenmodes. In previous papers [9–11] it was shown that the radial CAE structure is approximately described by a harmonic oscillator equation, where the effective potential is described by $V(r) = m^2/r^2 - \omega^2/V_A^2$, where m is the poloidal mode number. In toroidal geometry, this potential can form a well in both the radial and poloidal directions, depending on the shape of the density profile and the variation of the magnetic field intensity in the poloidal direction. If the potential forms a well, the solutions yield the eigenfrequency spectrum described by $\omega^2 = m^2 V_A^2/\kappa^2 r^2 (1 + k_\parallel^2 \kappa^2 r^2/m^2)[1 + (1 + 1/\sigma_i)(2s + 1)\Delta^2/r^2]$. The mode is localized to the potential well in both radial and poloidal directions. In this expression, s represents the radial wave number. The parameters κ and σ_i are geometric constants of order unity related to the radial and the poloidal structure of the potential well. The parameter Δ is a measure of the mode radial localization. The closed geometry in the toroidal direction also results in discrete values for the parallel wave number, $k_\parallel = (m - nq)/qR$. The toroidal wave number n provides the fine-scale splitting in the spectrum.

The mode drive comes from the perpendicular energy of super-Alfvénic NBI particles via particle-wave Doppler shifted cyclotron resonance [11]. The resonance is described by $\omega - k_\parallel V_{\parallel b} - k_\theta V_{dr} - l\omega_{cD} = 0$ for $l = 1$.

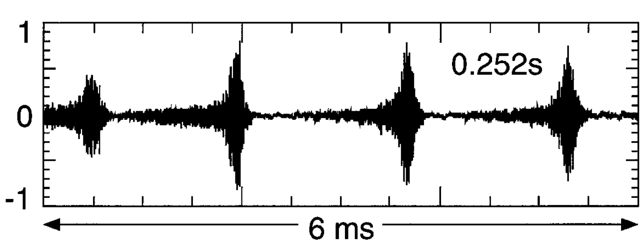

FIG. 5. Mirnov coil signals over a short time intrval showing the bursting character of the modes.

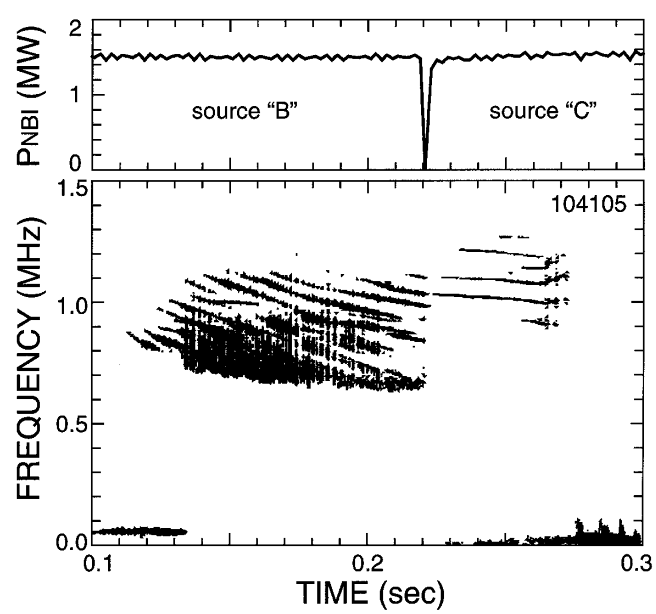

FIG. 6. Spectrogram of magnetic fluctuations through a switch from a shallower NBI to a deeper NBI source.

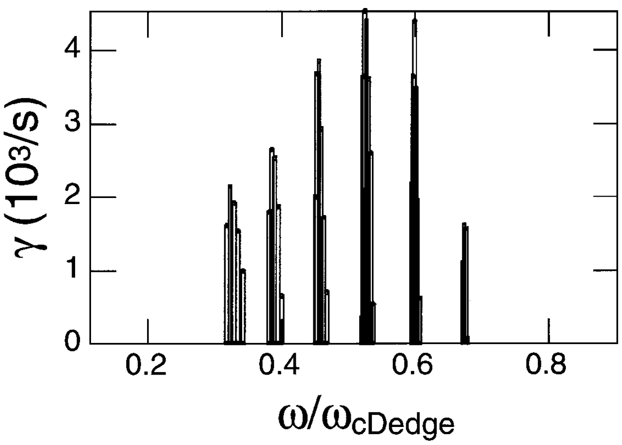

FIG. 7. Simulation of CAE modes showing the predicted multiple spectral peaks possible with this model.

The velocity space anisotropy of the beam ions creates a "bump-on-tail"–like distribution in the $v_\perp$ direction. The positive velocity gradient drives the CAE instability.

Simulations of the mode spectrum in simplified geometry have been done. The multiple "bunches" of peaks in the spectrum have been reproduced; however, only qualitative agreement with the observed mode spectrum has been found. A representative spectrum is shown in Fig. 7, where the parameter κ was adjusted to give the observed spacing of the bunches. A more complete simulation of the mode behavior is being pursued.

In summary, multiple, coherent modes at frequencies up to the deuterium ion cyclotron frequency were observed during neutral-beam injection heating of the NSTX. The modes were seen predominantly in the frequency range of 0.4–2.5 MHz. The modes are Alfvénic in character in that the mode frequency scales nearly linearly with magnetic field and inversely with the square root of the density. They have been identified as compressional Alfvén waves excited by a resonant interaction with the energetic beam ions. The modes are predicted to be localized near the plasma edge. The parametric scaling of the mode frequency with density and magnetic field is consistent with CAE modes. To date there has been no observation of enhanced beam ion loss associated with the mode activity. Rather, the presence of the modes may enhance the transfer of energy from the fast ions to the thermal electrons or ions [14].

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