PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76CH03073

PPPL-3617 **PPPL-3617**
UC-70

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by

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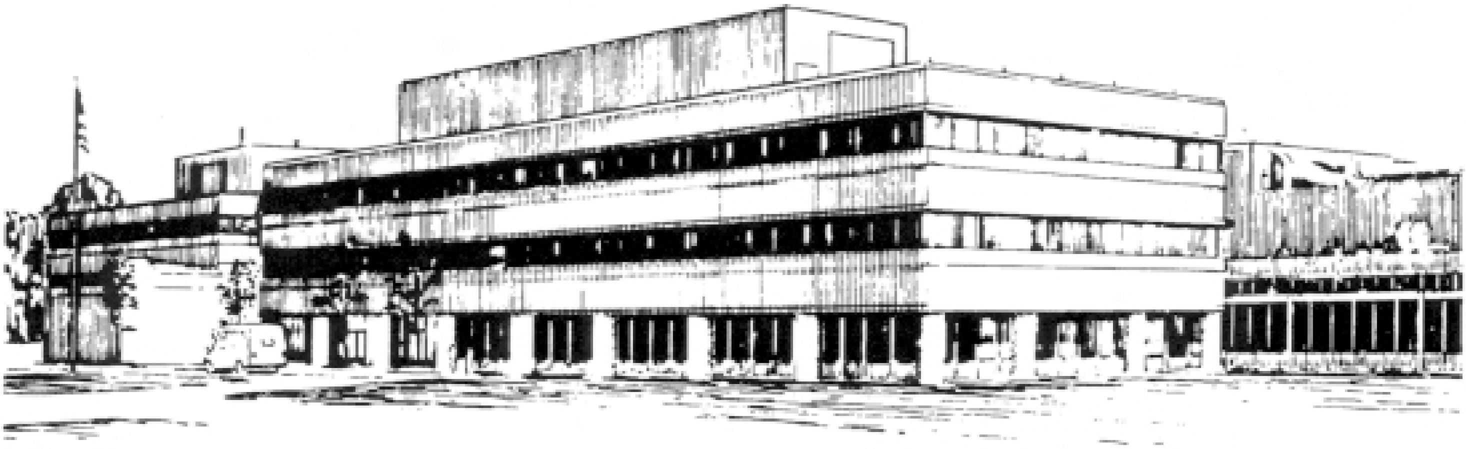
October 2001



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Observation of Beam Driven Modes during Neutral Beam Heating on the National Spherical Torus Experiment

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With the first injection of neutral beams on the National Spherical Torus Experiment (NSTX) [1], a broad and complicated spectrum of coherent modes was seen between ≈ 0.4 MHz and 2.5 MHz (where f_{ci} for deuterium is ≈ 2.2 MHz). The modes have been observed with high bandwidth magnetic pick-up coils and with a reflectometer. The parametric scaling of the mode frequency with density and magnetic field is consistent with Alfvénic modes (linear in B, inversely with the square root of density). These modes have been identified as magnetosonic waves or compressional Alfvén eigenmodes (CAE) excited by a cyclotron resonance with the neutral beam ions[2-4]. Modes have also been observed in the frequency range 50 - 150 kHz with toroidal mode numbers n = 1 - 5. These lower frequency modes are thought to be related to the TAE [5] seen commonly in tokamaks and driven by energetic fast ion populations resulting from ICRF and NBI heating. There is no clear indication of enhanced fast ion losses associated with the modes.

The NSTX is a low aspect ratio (R_{major}/r_{minor} ≈ 0.85 m / 0.65 m) toroidal device (ST). The range of operational parameters used for the experiments discussed here are: 0.7 - 1.0 MA of toroidal plasma current, toroidal field 0.3 - 0.45 T, central electron density of 1 - 5 x $10^{19}/m^3$, central electron temperature of up to ≈ 1 keV. The plasmas were heated with 1.5 - 3 MW of deuterium neutral beam injection (NBI) power at full energy of 70 - 80 keV.

A characteristic of STs is that the ratio of density to toroidal field is relatively high, and thus the Alfvén speed is relatively low compared to higher aspect ratio devices. As a result, the neutral beam injection energy on NSTX produces super-Alfvénic beam ions with velocities 2-4 times the Alfvén speed. This can provide a strong drive for various Alfvénic waves. A calculation of the beam deposition and slowing down with the TRANSP code predicts that the volume averaged beta of the beam injected ions is typically of order 20%. The NBI geometry and relatively large orbit size of the beam ions result in an anisotropic pitch angle distribution for the fast ions, providing an energy source to drive instabilities. Similar anisotropies are invoked to explain waves in the earth's magnetosphere[6,7].

The data shown in Figure 1 illustrates several common features of these modes. The modes onset 10 - 50 ms after the start of neutral beam injection. The mode frequencies drop with time. 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. In Fig. 1 it is seen 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 0.4 - 1.5 MHz and 1.5 – 2.5 MHz. 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.

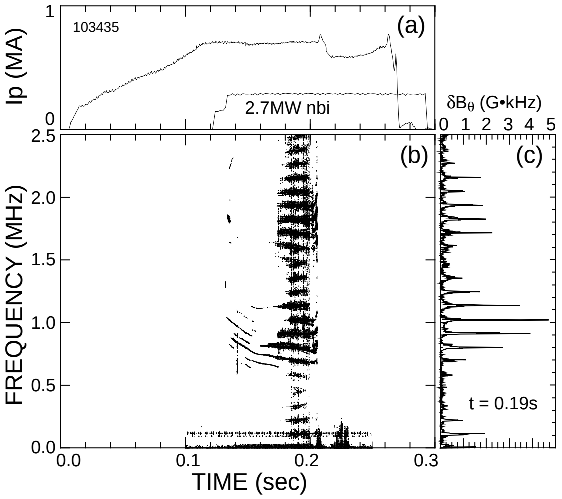

Fig. 1. Spectrogram of magnetic fluctuations.

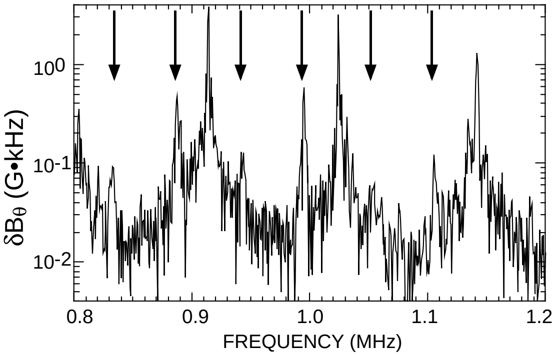

Fig. 2. Detailed spectrum showing fine structure.

In Fig. 2 is shown a higher resolution spectrum of the same data from 0.195 s. Each of the peaks now is seen to have satellite peaks shifted by ≈ 25 kHz. Detailed measurements of the mode localization have not yet been done. However the data from the reflectometer, which measures the displacement of constant density contours, shows that the mode does drive density fluctuations in the plasma (Fig. 3) as would be expected for a compressional Alfvén wave. While there is clear correlation of peaks in the spectra, the relative amplitude of the spectral peaks between the magnetic fluctuation data and the reflectometer data vary. The reflectometer measurement is localized near the plasma core vs. the edge location of the Mirnov coil measurements and the two diagnostics are measuring different parameters, so identical spectra would not be expected.

A lower limit for the growth and damping rates for the modes can be estimated from the bursting behavior sometimes seen. The period between bursts is ≈ 2 ms and the duration of each burst is 0.1 - 0.2 ms. In Fig. 4 is shown 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 ~ 0.15% of the mode frequency and the damping rate is comparable or slightly faster. Damping rates measured following beam turn-off are also in rough agreement with this estimate. An interesting observation is that all of the modes burst in unison, implying some strong coupling.

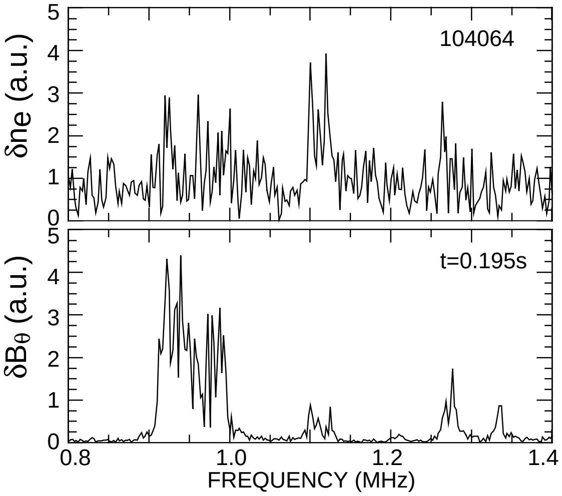

Fig. 3. Comparison of δB and density fluctuations.

The modes have been identified as compressional Alfvén eigenmodes[8]. In previous work [2-4] 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 yields the eigenfrequency spectrum described by $\omega^2 = m^2V_A^2/\kappa^2r^2\ (1 + k_{||}^2\kappa^2r^2/m^2)\ [1 + (1+1/\sigma_i)\ (2s+1)\ \Delta^2/r^2]$. The mode is localized to the potential well in both the radial and poloidal directions quantified by the parameters κ and σ_i which are geometric constants of order unity related to the radial and poloidal structure of the potential well. The parameter Δ is a measure of the mode radial localization and s is the radial wavenumber. The toroidal wave number n [$k_{||} = (m - nq)/qR$] provides the fine-scale splitting in the spectrum.

The mode drive is coming from the perpendicular energy of super-Alfvénic NBI particles via particle – wave Doppler shifted cylotron resonance [4]. The resonance is described by $\omega - k_{||}V_{||b} - k_\theta V_{dr} - l\ \omega_{cD} = 0$ for $l = 1$. 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.

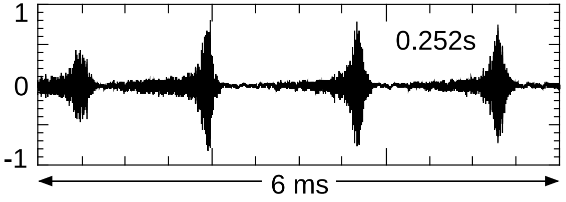

Fig. 4. Bursting character of CAE often seen.

The CAE modes are driven by the fast neutral beam fast ion population, but are Landau damped on primarily the electrons. However the possibility of additional damping on the ions is suggested by a previous experiment which documented stochastic ion heating by sub-ion cyclotron waves in a tokamak [9], and by recent theoretical work which has provided a new model for stochastic heating of ions [10]. It is possible to estimate the amount of heating power to the thermal population (ions or electrons) or conversely, the power extracted from the beam fast ion population by the waves. The power flow through the wave field is just the energy in the wave times the growth or damping rate, which are equal in saturation. While the mode amplitude in the plasma could be estimated from measurements of the internal density fluctuation level, such estimates are not currently available from the reflectometer. The growth or damping rate was estimated to be $\approx 10^4$/s from the bursting behavior sometimes seen. The energy density in the wave is about 4×10^{-9} $<\delta B^2(G)>$ MJ/m^3. For a plasma volume of ≈ 10 m^3 and the growth rate of 10^4/s, P_{heat} (MW) $\approx 4 \times 10^{-4}$ $<\delta B^2(G)>$, where is the average fluctuation amplitude of the sum of the waves over the entire plasma volume. Because these waves are relatively low frequency and weakly damped, a relatively large amplitude is required for significant heating, i.e., the average fluctuation level over the plasma volume must be ≈ 50 G for an integrated heating power of 1 MW.

In summary, multiple, coherent modes at frequencies up to the deuterium ion cyclotron frequency were observed during neutral beam injection heating of the National Spherical Torus Experiment (NSTX). The modes were seen predominantly in the frequency range of 0.4 kHz to 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[10].

We are grateful to the NSTX team for supporting these experiments. This work supported by U.S. DOE Contract DE-AC02-76CH03073 and Grant Nos. DE-FG03-99ER54527 and DE-FG03-86ER53225.

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