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

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With the first injection of neutral beams into the National Spherical Torus Experiment (NSTX) a broad spectrum of nearly equally spaced peaks in the frequency range from ≈ 0.2 to ≈ 1.2 ω_{ci} was observed. The frequencies have a scaling with toroidal field and plasma density consistent with Alfvén waves. From these and other observations, the modes have been identified as Compressional Alfvén Eigenmodes. Recent theoretical studies have proposed that CAE activity may contribute significantly to the heating of the solar corona. The CAE in NSTX may play a similar role in transferring energy directly from the beam ions to the thermal ions, a first experimental realization of alpha channeling.

I. INTRODUCTION

The practical realization of a fusion reactor based on magnetic confinement of a plasma will rely on the heating of the thermal plasma by super-Alfvénic ions (the 4.5 MeV alpha particles from the D-T fusion reaction). In such a reactor, the alphas slow down on and heat primarily the electrons. Collisions transfer energy from the electrons to the ions, supporting the fusion reaction. The energetic ions may also excite, through resonant interactions, a variety of mode activity such as Toroidal Alfvén Eigenmodes (TAE), Energetic Particle Modes (EPM), the fishbone instability and others. In some cases, the interaction of the alphas with these instabilities can induce loss or redistribution of energetic ions [1-8].

The EPM and TAE family of modes in the shear Alfven branch have been extensively studied in experiments on TFTR, JET, JT-60U and DIII-D. For the most part, these modes have been relatively benign, although the localized losses associated with the TAE driven by ICRF tail ions were considered responsible for minor damage to the TFTR vacuum vessel. The EPM were also, indirectly, implicated in affecting the performance of TFTR by inducing redistribution of the sawtooth stabilizing fast

ion component, leading to giant sawtooth crashes.

Compressional Alfvén modes excited by NBI fast ions were seen for the first time in NSTX during NBI heating experiments [9]. The CAE modes had been studied extensively theoretically and the ICE emission seen on TFTR and JET had been interpreted as a manifestation of CAE modes. Theoretical studies of the compressional Alfvén branch began with the goal of using this wave as a heating mechanism in tokamaks.

In cylindrical geometry, the spatial variation of the Alfvén velocity can provide the effect of a "potential well" for compressional Alfvén eigenmodes [10]. This cylindrical model has since been extended to toroidal geometry [11,12]. For the CAE the effective $k_{||}$ remains small and the electron and ion landau damping is weak and the drive from fast ions can destabilize the mode. A similar model has previously been invoked to explain the observation of ion cyclotron emission (ICE) from tokamak plasmas [13].

It has been suggested that certain wave particle interactions could be beneficial. If the waves excited by the alphas damped primarily on the thermal ions, this would directly "channel" the alpha energy to the thermal ion population [14,15], avoiding the more lossy electron channel. This model was called "Alpha Channeling". In Sect. IV we will examine the experimental data in an effort to find evidence of this alpha channeling.

A model for alpha channeling was proposed which would have application to tokamak fusion reactors and parts of which could have been tested on TFTR. These experiments, begun in the final year of operation of TFTR were inconclusive regarding the viability of the model.

In the model discussed here, the waves are naturally driven by the fast neutral beam ions. The damping would normally be weak, and on the thermal electrons. However, recent theoretical work on compressional Alfvén waves with respect to heating in the solar corona [16] and in STs [17] has suggested an alternative wave damping model. In this model, stochastic interactions of the thermal ions with a spectrum of waves can lead to stochastic heating of the thermal ions.

Similar stochastic ion heating by waves in the near sub ion cyclotron frequency range has previously been observed experimentally. In the Encore tokamak [18,19] a large amplitude drift-Alfvén wave with frequency of order half the ion cyclotron frequency (Ar II) was observed to cause strong heating through stochastic interactions of the thermal ions with the wave. This effect was numerically simulated and good agreement between

experiment and theoretical predictions was found.

II EXPERIMENTAL PARAMETERS

The National Spherical Torus Experiment (NSTX) is a low aspect ratio ($R_{major}/r_{minor} \approx$ 0.85 m / 0.65 m) toroidal device [20]. The mission of the experiment is to develop an empirical understanding of confinement and beta limiting MHD sufficient to form the basis for the design of a larger experiment. The experiments described here were performed in the first year of operation with neutral beam injection (NBI) heating.

The range of operational parameters used for the experiments discussed here are 0.7 to 1.0 MA of toroidal plasma current, 3.0 to 4.5 kG toroidal field, central electron density of 1-5 $10^{19}/m^3$, central electron temperature of up to ≈ 1 keV. The plasmas were heated with 1.5 to 3 MW of deuterium neutral beam injection (NBI) power at a full energy of 60 - 90 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 $V_b(80\ kV) \approx 2.8 \times 10^6$ m/s. The Alfvén velocity is $V_A \approx 0.9 \times 10^6$ m/s at an electron density of $3 \times 10^{19}/m^3$ and magnetic field of 3 kG (for a nominal deuterium plasma).

Motivated by the prediction that beam driven instabilities might be present at frequencies of order the ion cyclotron frequency (and lower), a high bandwidth array of magnetic pick-up (Mirnov) coils was installed on NSTX prior to the commencement of NBI heating experiments. The coils have an internal resonance at ≈ 4.4 MHz. With the added capacitance of the necessary leads, the bandwidth is reduced to ≈ 2.5 – 3 MHz. There are three coils in the array with a spacing of 10º and 30º in the toroidal direction. The coils are mounted on the vacuum vessel walls, approximately 20 cm outside the plasma.

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). The modes have been identified as magnetosonic waves or compressional Alfvén eigenmodes (CAE) excited by a cyclotron resonance with the neutral beam ions. There has been 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 [21]. At present there is only a limited amount of experimental data available for studying the poloidal, toroidal and radial structure of the modes.

III. CAE CHARACTERISTICS

In this section we present the characteristic features of the CAE and address the issue of the mode damping (and drive) rate, the fast ion resonance condition, mode amplitude and location. The data will be derived from an experiment whose goal was to determine the role of CAE in the inferred anomalous ion heating.

The principal experimental measurements leading to the identification of these fluctuations as being CAE have been presented in Ref. 9. It was shown that the mode frequency had an Alfvénic scaling ($\propto B/n^{1/2}$), the mode spectrum showed features consistent with theoretical models of the compressional Alfvén eigenmodes, and the modes were clearly driven by a fast ion population from neutral beam injection. It was also shown that the modes are a characteristic resonant frequency of the plasma, which is, at least linearly, weakly damped.

A typical example of CAE activity from this experiment is shown in Fig. 1. This is a spectrogram of voltage fluctuations (proportional to the time derivative of the poloidal magnetic field) on a Mirnov coil. In this example the deuterium ion cyclotron frequency is approximately 2.2 MHz on the outboard midplane. In an ST, the ω_{ci} is increases only slightly from the outboard midplan in to the magnetic axis.

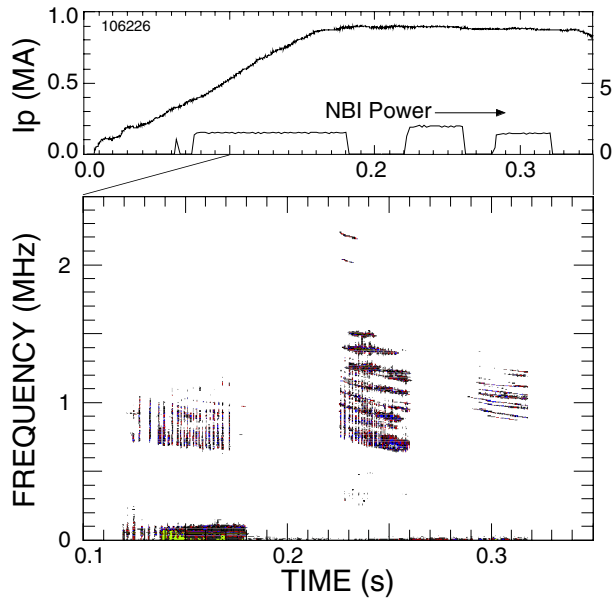

Fig. 1. Spectrogram of Mirnov coil fluctuations showing bursts of CAE activity for a typical discharge in this experiment.

A neutral beam source was injected during the current ramp to improve plasma reliability followed by two separate sources during the current flattop for 40 ms each. A 20-40 msec ohmic period was included to provide background data for the CHERS ion temperature measurement. The purpose of the beam pulses was to excite the CAE activity and provide for two CHERS measurements of the ion temperature profile (each measurement is integrated over 20 ms and at this time the analysis used the backgrounds measured before and after each pulse). Thus, during each beam pulse there is a measurement of the ion temperature and rate of change.

The mode frequency falls with rising density. The drop is visible especially during the beam pulses from 0.22 to 0.26 s and 0.28 – 032 s. The drop is consistent with the rise in plasma density. The modes may have a bursting character as is seen during the first and second beam pulses, or be quasi-continuous as during the third pulse.

A detail of the CAE activity at the end of the second beam pulse is shown in Fig. 2. There are only a few modes visible here, and the contour plot suggests that the width of each spectral peak is relatively small.

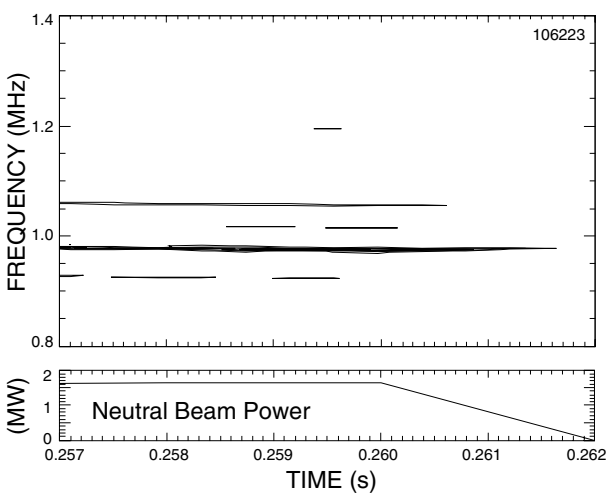

Fig. 2. Detail of Mirnov coil spectrogram showing mode damping at end of NBI injection.

Following the turn-off of the NBI source, the modes decay rather rapidly. In Fig. 3 is shown the rms fluctuation level between 0.95 and 1 MHz through a time period encompassing the mode decay. The mode damping rate is of order 1.5 x 10^3 /s. This should be considered a lower bound on the damping rate as there may still be fast ion drive present during this period.

The quick decay of the mode, compared to the much longer classical beam slowing down time of order 30 - 40 ms, suggests that the modes are driven by a relatively small fraction of the beam ions. This partition could be in energy, e.g., only the most energetic ions near the injection energy drive the mode. The partition could also be a localization in physical or fast ion phase space. Nevertheless, the modes apparently rapidly deplete this small population of fast ions, after which they are not replaced. In data presented later, it will indeed be shown that the fast ion resonance drive condition is very sensitive to beam energy.

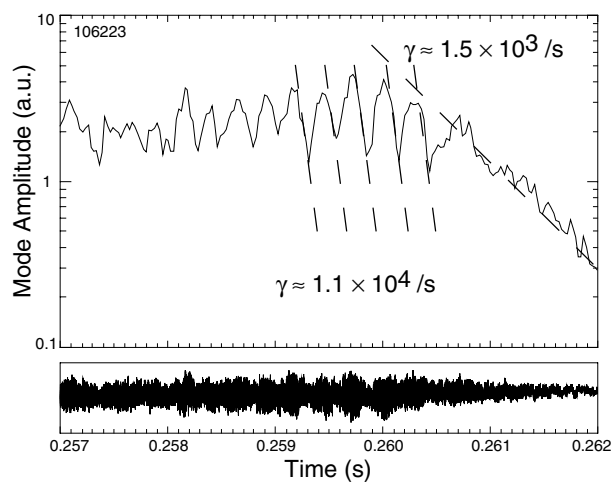

Fig. 3. Mode amplitude showing exponential decay after NBI turns off at 0.26s. Decay rate of bursts is also indicated.

Prior to beam turn-off in Fig. 3, the mode amplitude has a bursting character. The growth and damping rate for the mode for

these bursts is considerably faster than the decay after beam turn-off, perhaps of order 1.5 x 10^4 /s. The bursts only modulate the mode amplitude by about 50%. This mode damping may be a manifestation of a strong threshold in a stochastic ion damping or scattering model.

A single spectrum from the spectrogram in Fig. 3 is shown in Fig. 4 at the time of 0.26 s. The Fourier transform is calculated over a time period spanning roughly 0.8 ms. The half width at half maximum of the dominant peak is about 3 kHz. Approximately 1 kHz of this width derives from the slow frequency change (1-2 kHz/s) over the 0.8 ms Fourier transform window. For weakly damped resonant systems, the half width in the resonant frequency response is approximately the damping coefficient, $\gamma \approx \delta\omega / 2$. Thus, we can

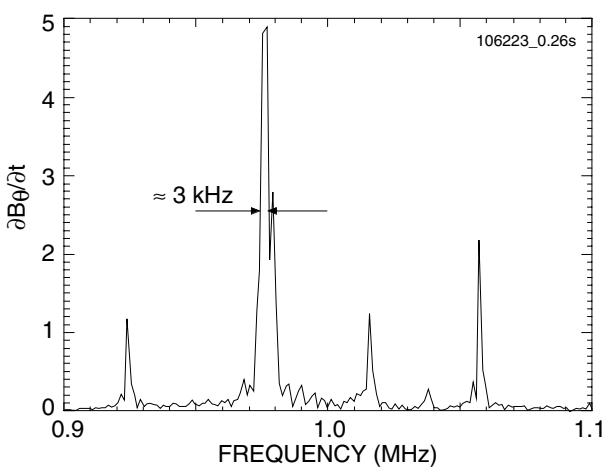

Fig. 4. Single spectra from Fig. 3 at 0.26s.

estimate the damping on these modes to be less than about 3 x 10^3 /s, consistent with the lower limit on mode decay rate measured after beam turn-off.

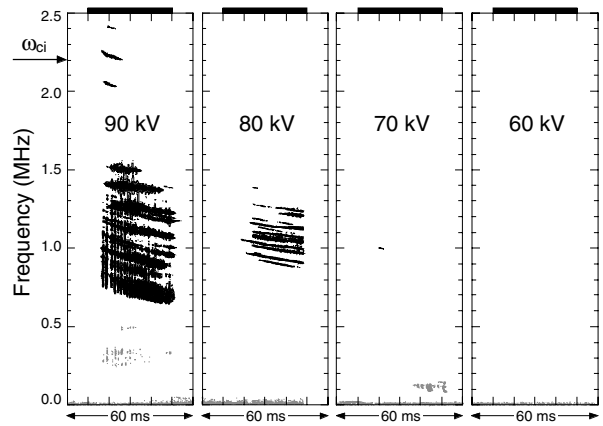

Fig. 5. Spectrograms of Mirnov coil data taken during four neutral beam pulses. The neutral beam injection energy varied from ≈90kV to ≈60kV. The pulse duration is indicated by the black bar at the top of each spectrogram.

The rapid decay of the modes following beam turn-off suggests that the resonance drive condition for the modes requires beam ions close to or greater than the beam injection energy of 80 kV. This was confirmed by an experiment where the beam injection energy was varied from ≈ 90 kV to ≈ 60 kV. Spectrograms of Mirnov coil data taken during neutral beam injection pulses with fast ion energies of 90, 80, 70 and 60 kV are compared in Fig. 5. The 90 kV beam excited larger and more CAE modes than at 80 kV. At 70 kV there was only one visible brief mode and at 60 kV there are no visible modes.

The qualitative data from Fig. 5 is shown more quantitatively in Fig. 6 where the rms magnetic fluctuation level vs. the beam

injection voltage is shown for 19 NBI pulses. An energy threshold for excitation of the modes is found at about 70 kV. Likewise, this result suggests that the modes can access at most 10-15 % of the beam power.

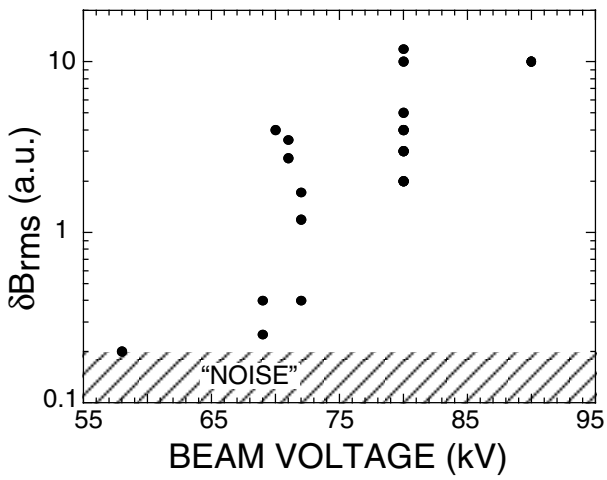

Fig. 6. Peak RMS fluctuation level during a beam pulse vs. the beam injection voltage. A threshold for mode excitation is seen at about 70 kV.

The beam voltage scan also provides an opportunity to compare the scaling of the measured neutron rate with beam injection voltage. The neutron detector is approximately calibrated, but the TRANSP prediction of the neutron rate was lower than that measured. In Fig. 7 the measured rate at 60, 70, 80 and 90 kV beam injection energy is compared to the TRANSP modeling. The TRANSP rate was scaled by ≈ 1.4 to fit the measured rate. The good agreement in neutron evolution and peak levels during NBI suggests that the CAE activity is not having a strong affect on the beam slowing down or fast ion confinement. In fact, TRANSP predicts a faster drop in neutron rate at each beam turn-off than is seen in the experiment.

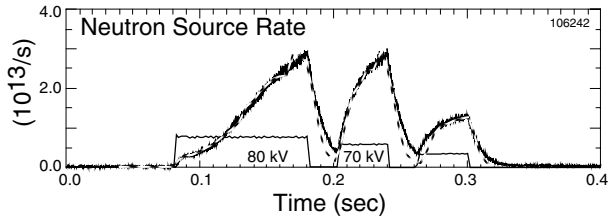

Fig. 7. Relative comparison of the measured neutron rate evolution to that simulated with TRANSP. The TRANSP simulation has been scaled by 1.4. The last beam pulse was at ≈60 kV.

The change in the fast ion velocity between weak drive at 70 kV and strong drive at 80 kV is only about 6%. There is a much larger change in the $V_{Alfvén}$, thus $V_{beam}/V_{Alfvén}$, during the evolution of any discharge due to the increase in density. Likewise the change in beam deposition profile should be modest for that change in voltage. This sensitivity to the beam voltage is not understood as yet.

V. ION HEATING

Power balance calculations using the TRANSP code [22] find that the ion temperature is anomalously high [23]. The TRANSP code finds, assuming classical beam fast ion power deposition, that the inferred ion heat transport, is negative, implying a flow of power to the ions through a channel not included in the analysis. The CAE activity might directly transfer energy from the beam

ions to the thermal ions; a power flow channel not incorporated in the TRANSP code.

The possible role of the CAE in the power balance calculation can be estimated in several ways. However, without a measurement of the mode amplitude, it is necessary to rely directly on power balance calculations. In the first approach, we will estimate the necessary incremental ion heating necessary to allow ion thermal diffusivity to be of order the neoclassical estimates. In a second approach, TRANSP uses the electron density and temperature profiles to calculate χ_e, but simulates the evolution of the ion temperature profile with an assumption about the ion transport.

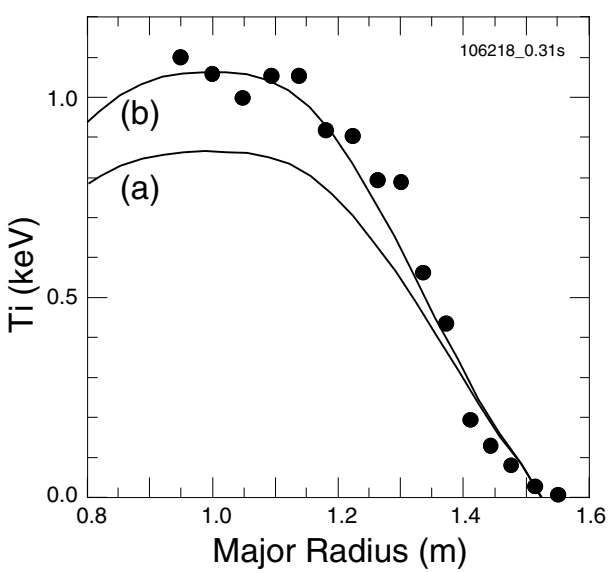

Fig. 8. Comparison of measured ion temperature (solid circles) with TRANSP simulated ion temperature using, a) neoclassical thermal diffusivity, b) neoclassical thermal diffusivity with 50% of NBI power to electrons diverted to ions.

We begin with the pair of shots used for Fig.5 in which the beam voltage was scanned from 90 to 60 kV. The TRANSP code has been used to analyze these shots using different approaches. In Fig. 8 are compared the measured ion temperature profile, and that simulated with TRANSP, assuming that the ion transport is neoclassical (curve labeled "a"). The analysis is for the 80 kV beam case shown in Fig. 5, i.e., a case with a moderate level of CAE activity. The ion temperature is everywhere measured to be higher than the neoclassical (most optimistic) simulated temperature.

TRANSP typically calculates that approximately two thirds of the beam power is deposited in the electrons, and one third in the ions. It is possible in TRANSP to arbitrarily reapportion this beam power. The second simulation, labeled "b", in Fig. 8 shows the ion temperature assuming that 50% of the beam power to the electrons is instead deposited in the ions. Through this crude tool we estimate that it is necessary to divert about half of the initial beam power from the electrons to the ions, or about 400 kW, in this shot to match the measured ion temperature.

The second example is the 60 kV case from Fig. 5 which had no detected CAE activity. The measured ion temperature (solid circles) compared to the neoclassical TRANSP

simulation (curve labeled "a") is shown in Fig. 9. The ions are again a few hundred eV hotter than the electrons, and well above the neoclassical simulation of the ion temperature. In this case, though, diverting 50% of the beam power from the electrons to the ions results in a predicted ion temperature still much lower than the measured ion temperature (curve labeled "b"). Diverting the total beam power to the ions was also insufficient to match the measured ion temperature profile.

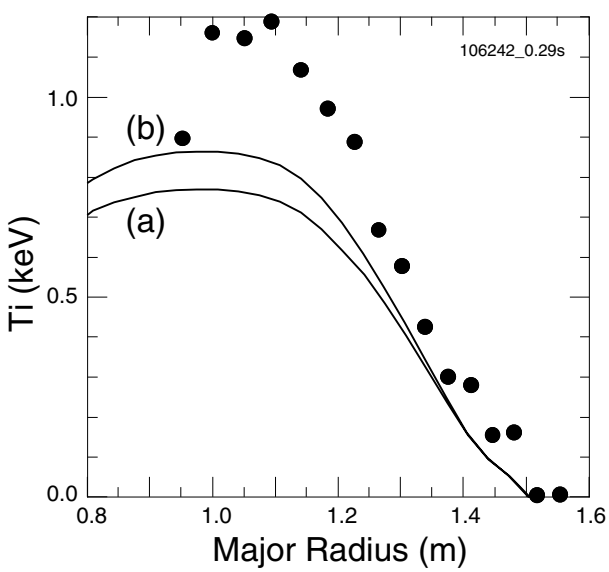

Fig. 9. Comparison of measured ion temperature (solid circles) with TRANSP simulated ion temperature using, a) neoclassical thermal diffusivity, b) neoclassical thermal diffusivity with 50% of NBI power to electrons diverted to ions.

A more direct estimate of the necessary incremental heating to the ions can be found by using the measured ion temperature profile to evaluate the ion conductive power flow. The necessary incremental power density to the ions is approximately the conductive power. The profile of conductive power is shown for the 60 kV case in Fig 10. The peak necessary incremental heating power density is ≈ 0.1 to 0.15 MW/m^3. The integrated incremental heating power for this case is greater than 1 MW (compared to ≈ 0.4 MW in the 80 kV example). This is greater than the total injected heating power of ≈ 0.6 MW.

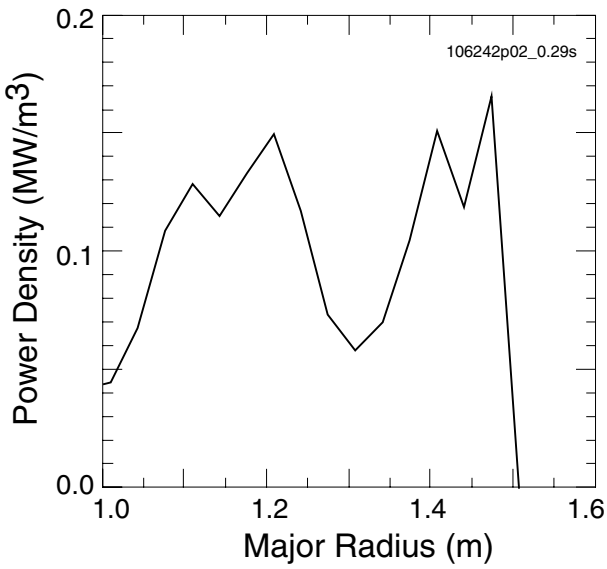

Fig. 10. Estimated incremental power density to ions necessary to achieve power balance.

To summarize, the anomalously high ion temperature is observed in plasmas with and without detectable CAE activity. Further, the inferred deficit in ion heating power for the non-CAE case is greater than the total neutral beam heating power. Thus, the modes observed in the higher voltage shots cannot be regarded as being responsible for the observation of anomalously high ion temperatures.

VI. SUMMARY

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.

Previous experiments and recent theoretical work have suggested that modes in this frequency range can stochastically heat the ions, possibly explaining the anomalously high ion temperatures observed on NSTX. In this paper we have shown the observed CAE modes apparently are driven by only the most energetic beam ions (> 70 kV for deuterium). This is consistent with the observation of no significant effect on the neutron emission in the presence of CAE activity. The coherence of the individual instabilities (line widths of less than 2-3 kHz) suggest a very weakly damped plasma resonance (Q > 300). This is also consistent with observed decay rates for the modes of 0.2 – 2 x 10^4 /s.

These conclusions are based on a relatively small data set. In future experiments the power balance analysis calculations will be more carefully explored. Improvements in the diagnostic systems will extend bandwidth to higher frequencies and hopefully improve sensitivity as well obtain absolute internal measurements of the mode amplitude.

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