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# The effect of MHD instabilities on performance of the National Spherical Torus Experiment

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The National Spherical Torus Experiment (NSTX) [1] is a low aspect ratio (R/a ≈ 1.3) toroidal device. The plasma major and minor radii are 0.8 m and 0.65 m respectively. The operational parameters for this experiment are up to 1.5 MA of plasma current, 3 to 6 kG toroidal field, central electron density is 0.5 - 8 x $10^{19}/m^3$, central electron temperature of 0.3 – 4 keV. The plasmas were heated with 0.5 to 6 MW of deuterium neutral beam injection power at a voltage of up to 100 kV.

NSTX performance is affected/limited by the full range of MHD instabilities seen in conventional aspect ratio tokamaks. External kinks (pressure and current driven), internal kinks, tearing modes, sawteeth, ELMs have all been seen on NSTX [2]. ST's in general, and NSTX in particular, are susceptible to fast ion driven instabilities due to the relatively low toroidal field. Indeed, a wide variety of beam driven instabilities has been seen in NSTX at frequencies ranging from 10's of kHz to many MHz. The Alfvénic modes are readily excited in NSTX as the neutral beam full energy ion velocity is typically 2-4 times the Alfvén speed

This paper will discuss three beam driven instabilities commonly seen on NSTX; TAE or EPM modes, fishbone-type instabilities, and CAE modes. There are, additionally, a coterie of other, as yet, less well identified modes, discussion of which is beyond the scope of this paper. Also of interest, the large fast ion population in NSTX plasmas does not stabilize the sawtooth instability.

An example of a typical spectrum of MHD activity in the frequency range up to 150 kHz during NBI on NSTX is shown in Fig. 1. This range includes the EPM, TAE, and fishbone, but excludes the "compressional" Alfvénic mode (CAE) activity.

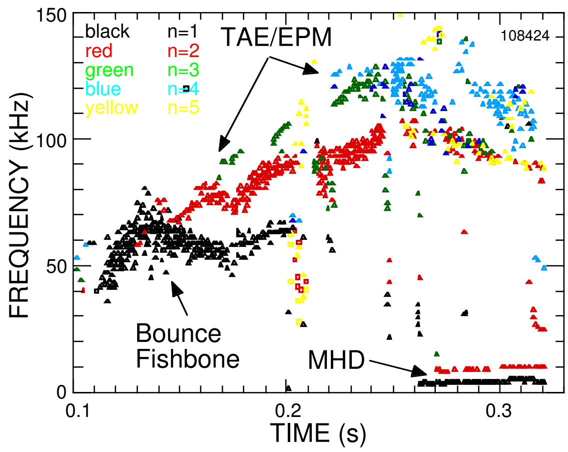


Fig. 1 Spectrogram of Mirnov coil signal.

The first shear Alfvénic gap, the toroidal Alfvén eigenmode gap, for NSTX occurs at frequencies between about 50 and 150 kHz. In this frequency range, in Fig. 1, there are several different coherent fluctuations. Some of the modes show a "chirping" character where the frequency drops by a factor of ≈ 2 in less than $10^{-3}$ s. These observations are not dissimilar to the experience on START [3].

These instabilities have, for the most part, an insignificant affect on fast ion confinement or performance. One exception is that bursts of TAE modes have, in some cases, been well correlated with abrupt neutron rate drops, of order 5 – 10%, and expulsion of fast ions.

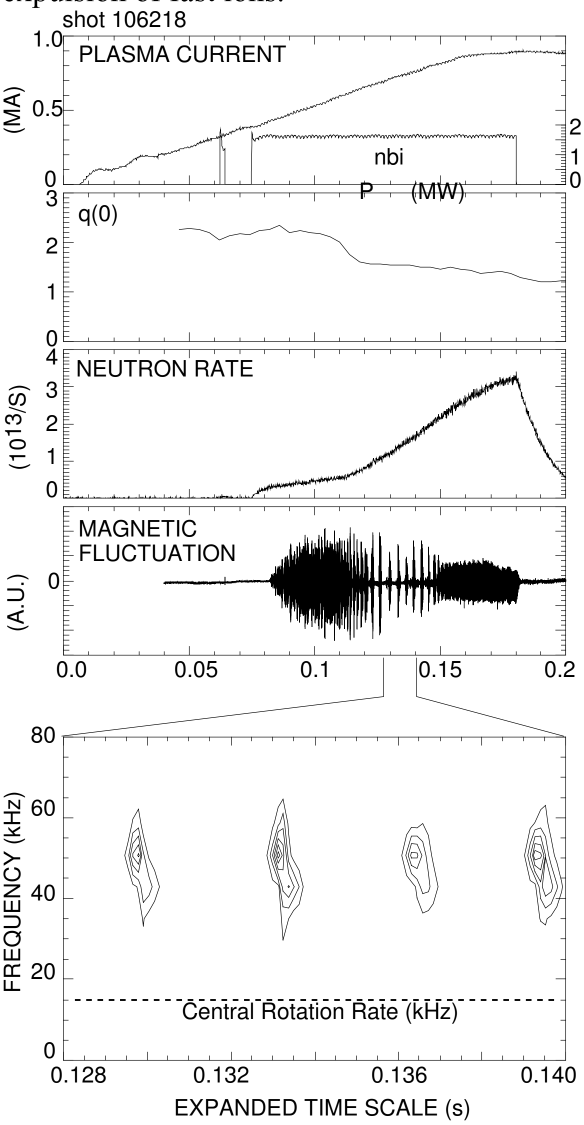


Fig. 2 Waveforms showing appearance of bounce-resonance fishbone instability.

**Bounce fishbone modes** - The chirping modes with toroidal mode number n = 1 are believed to be a new variant of the precession resonance fishbone mode [4,5] commonly observed in conventional aspect ratio tokamaks. The modes occur when the central q is believed to be well above unity. The fast ion resonance condition is no longer the precession drift frequency, but at the fast ion bounce frequency [6].

In Fig. 2 is shown a bounce fishbone observed on NSTX. The bounce-resonance fishbones (bfb), begin when the inferred q0) has dropped to ≈ 1.7. Subtracting the plasma central rotation rate, it is seen that the plasma-frame frequency of the mode chirps downward from about 45 kHz to 25 kHz. In Fig. 3 this range of chirping is compared to the bounce frequencies (from the ORBIT code) for the fast ion distribution calculated with TRANSP. The modes are seen to be resonant with the large population of beam ions with energies between 10 and 30 kV.

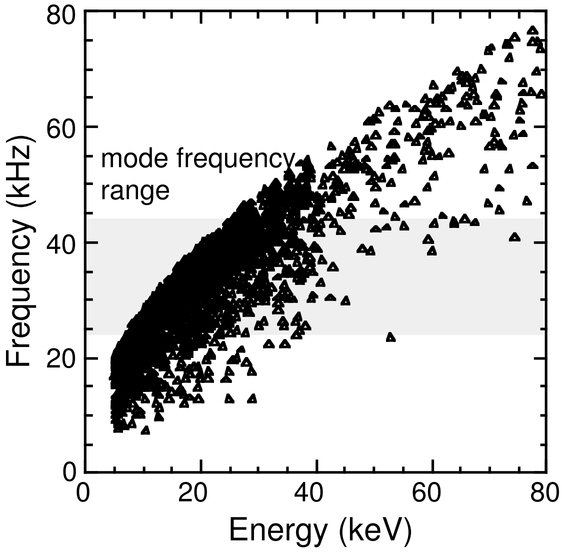


Fig. 3. Calculated distribution of fast ion bounce frequencies (ORBIT and TRANSP).

The modes appear relatively weak; they are barely detectable in the soft x-ray emission and there is not a measurable affect on the neutron rate, implying no strong loss of fast ions.

This observation of bounce resonance fishbones has implications for conventional aspect ratio reactors in that the drift reversal expected to stabilize the fishbone instability may no longer be sufficient if the fast ion distribution has a fast ion population such that the average bounce angle is large, allowing resonance at the bounce frequency to drive the modes.

**TAE fast ion loss** - The non-chirping modes, in Fig. 1, typically with toroidal mode number between 2 and 6, are assumed to be TAE modes [7]. A somewhat surprising observation is that, unlike beam driven TAE modes in conventional aspect ratio tokamaks, these modes generally seem to have a relatively small affect on the fast ion population. No obvious impact is seen on the neutron rate, nor is there an increase in the measured fast ion loss. These modes don't burst, appearing more like the ICRF driven TAE modes seen in TFTR.

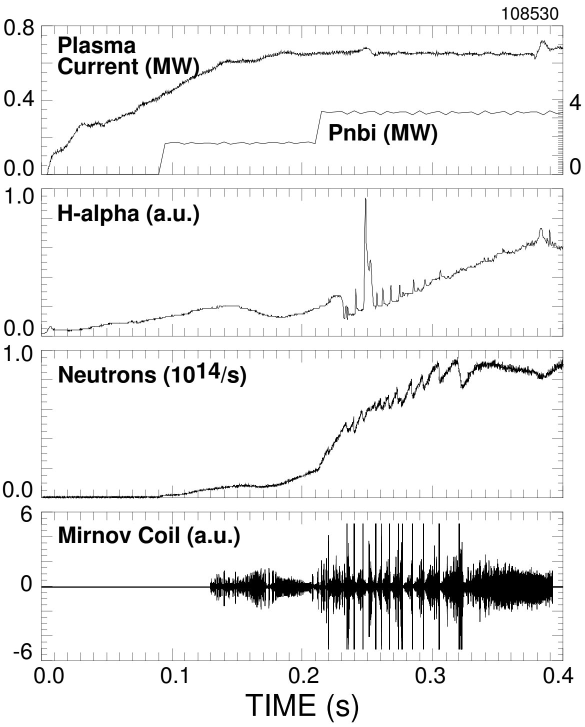


Fig. 4 Waveforms showing appearance of bursting TAE modes and fast neutron drops.

However, in plasma conditions in which the central q is high and the beam heating is intense, the TAE evolve from continuous modes to bursting modes, with multiple modes of different n present. When the multiple n number bursting TAE modes are present, significant fast ion losses are observed. In Fig. 4 are shown waveforms of the plasma current, magnetic fluctuations as measured with a Mirnov coil, neutron rate, and $D_\alpha$ light.

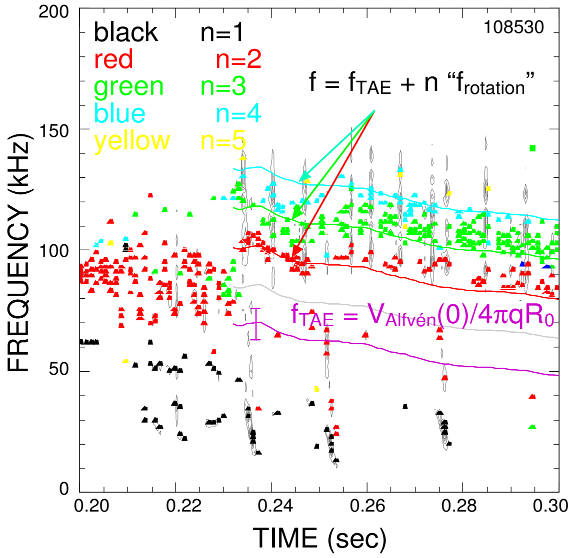


Fig. 5 Spectrogram and mode identification of TAE and other modes.

Coincident with the strong magnetic fluctuation bursts, sharp drops in the neutron rate, and increases in the Da light are seen. These observations are consistent with losses of 5 – 10% of the most energetic fast ion population.

In Figure 5 is shown a spectrogram of magnetic fluctuations with an overlay of symbols indicating the toroidal mode numbers. The MHD bursts which are correlated with the fast ion losses are indicated by vertical dashed lines. As can be seen, the bursts appear to consist of several modes with n ranging from 2 to 4.

**Compressional Alfvén Waves** - The compressional Alfvén waves are believed to have a relatively unique structure in low aspect ratio devices [8-11]. The strong gradient in toroidal field from the inboard to outboard plasma edge translates to a strong poloidal gradient in magnetic field strength. As a result, the modes can end up localized in a " well" on the outboard edge of the plasma. The experimental observations of the CAE mode are, so far, in good agreement with the predicted mode characteristics.

It was predicted that multiple CAE modes at sufficient amplitude could stochastically heat the thermal ions [12,13]. Coupled with an apparently anomalously high ion/electron temperature ratio in NSTX, this has encouraged study of the CAE modes [14].

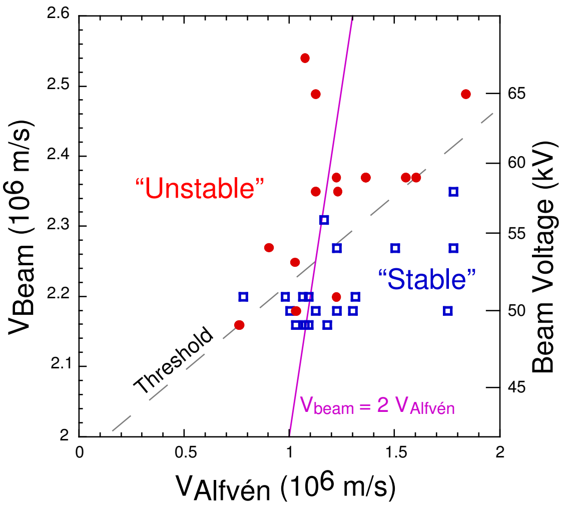


Fig. 6 Beam energy threshold for CAE excitation.

Experiments designed to place constraints on the fraction of beam energy available to drive the CAE instability have demonstrated that it is not likely that the *observed* CAE modes can be responsible entirely for the high ion/electron temperature ratio. There is a clear threshold in beam energy necessary to trigger these CAE instabilities. The threshold has a strong offset linear dependence on beam voltage and toroidal field (Fig. 6). The threshold is more complicated than a simple $V_{beam}/V_{Alfvén}$ threshold.

For typical NSTX parameters, the beam energy threshold is at least 55 kV. With only 66% of the beam power in the full-energy component, this means that less than ≈ 20% of the power of 80 kV beams is available to drive the CAE. As the 60-80 kV beam population is disproportionately responsible for the neutron production, a symptom of significant CAE-ion heating would be lower than expected neutron rate and a faster decay of the neutron rate following the end of NBI, neither of which is seen.

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