NSTX FY 2007 Joule Milestone Fourth Quarter and Final Year-End Report
September 2007

Joule Milestone: *"In FY 2007 FES will measure and identify magnetic modes on NSTX that are driven by energetic ions traveling faster than the speed of magnetic perturbations (Alfvén speed); such modes are expected in burning plasmas such as ITER."*

Q1 Joule Target: Dec. 31, 2006: *At the NSTX Research Forum, complete development of a plan for the NSTX research campaign to study magnetic modes driven by energetic particles*. (12/30/06: Achieved on schedule)

Q2 Joule Target: Commission and calibrate diagnostics tools and data acquisition hardware on the NSTX device. (3/31/07: Achieved on schedule)

Q3 Joule Target: Measure supra-Alfvénic fast ion driven magnetic modes, covering frequencies up to a substantial fraction of the deuterium ion gyrofrequency. (6/22/07: Achieved on schedule)

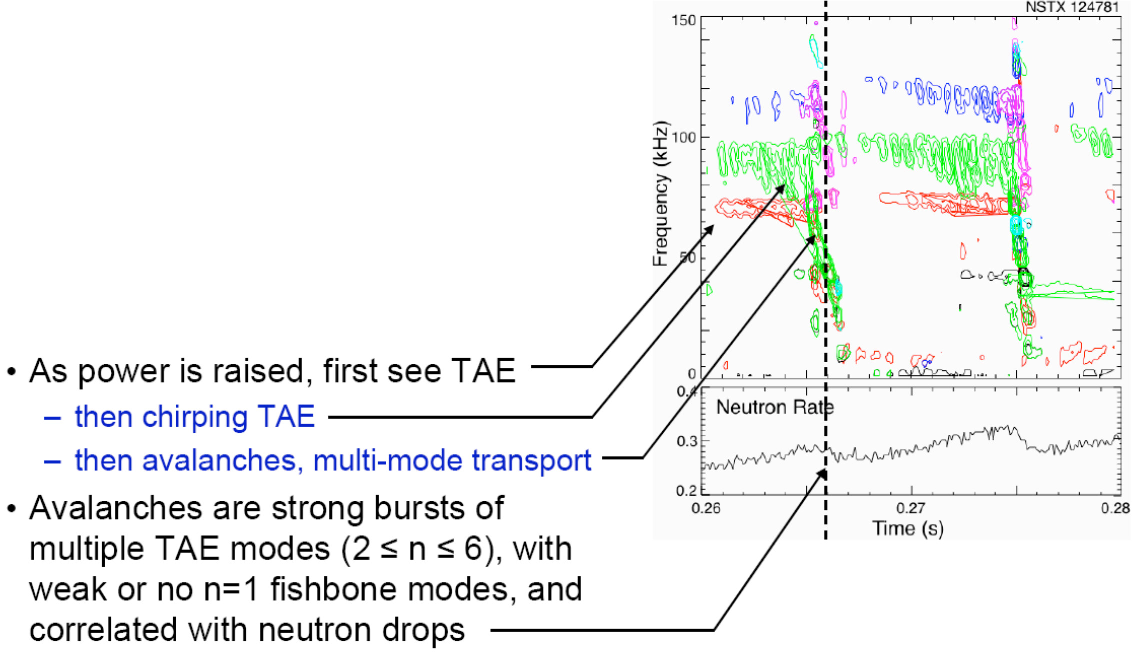
Q4 Joule Target: Identify magnetic modes and mode behaviors associated with super-Alfvénic fast ions and compare with modes associated with sub-Alfvénic fast ions published in the literature. (9/30/07: Achieved on schedule)

Report of Fourth Quarter Joule Target and Joule Milestone Completion:

To complete the NSTX FY 07 Joule milestone, a series of energetic particle related experiments and analyses were performed on NSTX and the Q4 Joule Target of *"Identify magnetic modes and mode behaviors associated with super-Alfvénic fast ions and compare with modes associated with sub-Alfvénic fast ions published in the literature"* and the FY 07 Joule Milestone of *"In FY 2007 FES will measure and identify magnetic modes on NSTX that are driven by energetic ions traveling faster than the speed of magnetic perturbations (Alfvén speed); such modes are expected in burning plasmas such as ITER."* were successfully achieved on schedule. The results have been reported in an invited talk and contributed presentations at recent the EPS meeting (N. N. Gorelenkov, et al. and E. Fredrickson et al., Proc.for the 34th European Society Conference on Plasma Physics, Warsaw, Poland June, 2007) and the results will be also reported in a number of invited and contributed papers at the upcoming APS meeting in November 2007, Orlando, Florida.

The experimental proposals planned and carried out during the FY 07 plasma operation were "Direct Measurement of MHD-induced Energetic Ion Redistribution in Space and Energy by Neutral Particle Analyzer Vertical Scanning", "Beta suppression of Alfvén cascades", "Beta induced Alfven acoustic modes", "Multi-mode beam fast ion loss power scan" and "Investigation of Ion Transport with Beam Modulation".

The instabilities most clearly associated with super-Alfvénic fast ions in NSTX have been identified as three branches of various Alfvén Eigenmodes (AEs), such as Toroidal Alfvén Eigenmodes (TAEs), Reversed Shear Alfvén Eigenmodes (RSAEs), and Beta induced Alfvén-acoustic Eigenmodes (BAAEs). Importantly, in 2007 experiments, the entire AE stability space - from no AE modes to AE avalanche threshold – has been mapped and comprehensively diagnosed for the first time in NSTX. This mapping was achieved by varying the NBI source voltage (power) and diagnosing the AE modes and the effects of the modes on fast-ions and the bulk plasma. A single NSTX NBI source operating at its lowest voltage (≈ 62 kV) was found to be just below the linear threshold for exciting TAE and BAAE instabilities. As shown in Figure 1 below, as the fast ion pressure is increased above threshold following beam turn-on, mode onset is observed, followed by frequency chirping of the modes as the fast ion pressure increases. As the input power (and fast-ion pressure) is further increased, multiple AE modes which overlap in frequency are excited leading to a burst of rapid fast-ion transport/loss and an associated decrease in neutron rate. Note here that the inference of rapid fast-ion transport/loss is made possible by the fact that most neutrons in NSTX are produced via beam-target fusion reactions.



- As power is raised, first see TAE
  - then chirping TAE
  - then avalanches, multi-mode transport
- Avalanches are strong bursts of multiple TAE modes ($2 \leq n \leq 6$), with weak or no n=1 fishbone modes, and correlated with neutron drops

Figure 1 - Time history of magnetic field activity, tentatively identified as TAEs, showing onset, chirping, and avalanche event with multi-mode transport of fast ions and associated neutron rate decrease.

A critical issue for ITER and CTF is to what extent TAE instabilities can lead to redistribution and/or loss of the fast-ions. Redistribution can modify the heating profile from the fast ions and the profile of the driven current from neutral beams. Loss can reduce the heating from fast ions and potentially damage the reactor walls. Figure 2 shows the NSTX fast-ion operating space – including the onset and avalanche thresholds described above – overlaid with the operating spaces of reference devices of interest including ITER, CTF, ARIES-ST, and DIII-D.

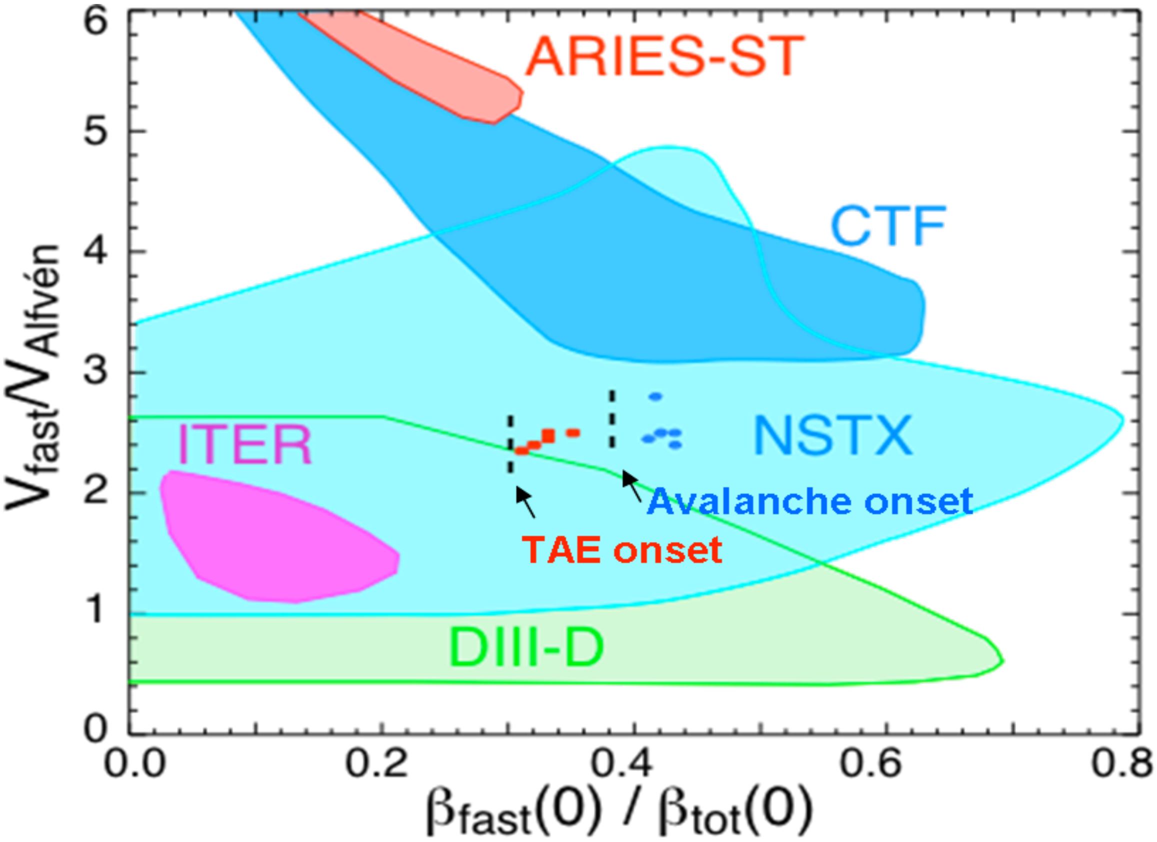


Figure 2 - NSTX TAE stability space overlayed with the parameter space of other tokamak and ST devices of interest.

Several features are note-worthy in Figure 2. First, we note that the normalized fast-ion velocity V_{fast}/V_{Alfven} for NSTX is comparable to the upper end of the value range for ITER, whereas the NSTX fast-ion pressure ratio β_{fast}/β_{tot} at TAE onset significantly exceeds β_{fast}/β_{tot} for ITER. It is important to note that the fast-ion operating space shown for ITER in Figure 2 does not include fast-ion pressure from NBI, i.e. only alpha-particles are included. Consistent with NOVA-K calculations, ITER is in fact predicted to be stable to TAE modes if the fast-ion pressure is only comprised of alpha particles. (For more information, please see PPPL theory Joule milestone of FY07. [http://w3.pppl.gov/theory-main/PublicTheoryPage/Joule_Milestone.html]). However, if NBI fast-ions are included and the associated fast-ion pressure ratio (β_{fast}/β_{tot}) is increased closer to NSTX TAE onset values, TAE modes are also predicted to become marginally unstable in ITER. Thus, the NSTX TAE results described above are qualitatively consistent with expectations for ITER.

Figure 2 also shows that CTF operates in a significantly different fast-ion regime than ITER. CTF is even farther above the velocity-space instability threshold $V_{fast}/V_{Alfven} \approx 1$ and has a significantly higher fast-ion pressure ratio β_{fast}/β_{tot}. We note that CTF could potentially operate with β_{fast}/β_{tot} far above the NSTX TAE avalanche onset threshold. Thus, TAE avalanches could in fact be common in an ST-based CTF. The higher values of V_{fast}/V_{Alfven} in CTF relative to NSTX would presumably further increase the instability drive, making such avalanche conditions and associated alpha particle radial transport even more likely. Clearly, a critical question for CTF is how such avalanches might influence the NBI fast-ion current drive, and the confinement of fast-ions overall.

Previously published studies in NSTX investigating low-frequency (sub-Alfvénic) MHD activity have shown that significant fast-ion redistribution and loss can occur if mode amplitudes are sufficiently large. In particular, it was shown that the NBI current drive profile could be significantly modified by such instability activity. Similar analysis has now begun for the super-Alfvénic fast-ion-driven AE instabilities described above, and based on present understanding, significant redistribution/loss of current from TAE activity is only expected to occur during strong avalanche conditions.

Modifications of the current profile due to mode activity can in principle be inferred from comparison of the measured q profile (using MSE constrained reconstructions) to that predicted assuming neoclassical resistive diffusion of the inductive current, neoclassical bootstrap current, and classical fast-ion slowing down expected in the absence of TAE and/or MHD activity. Figure 3 below shows a comparison of the measured q profile during TAE avalanche activity to that predicted by TRANSP ignoring any effects of fast-ion instabilities. Differences in the q profile are observed in the plasma core, which is a potentially important finding – however many additional sensitivity studies are needed to firmly conclude that AE avalanches are modifying the NBI current profile, and such studies are an ongoing and active area of research.

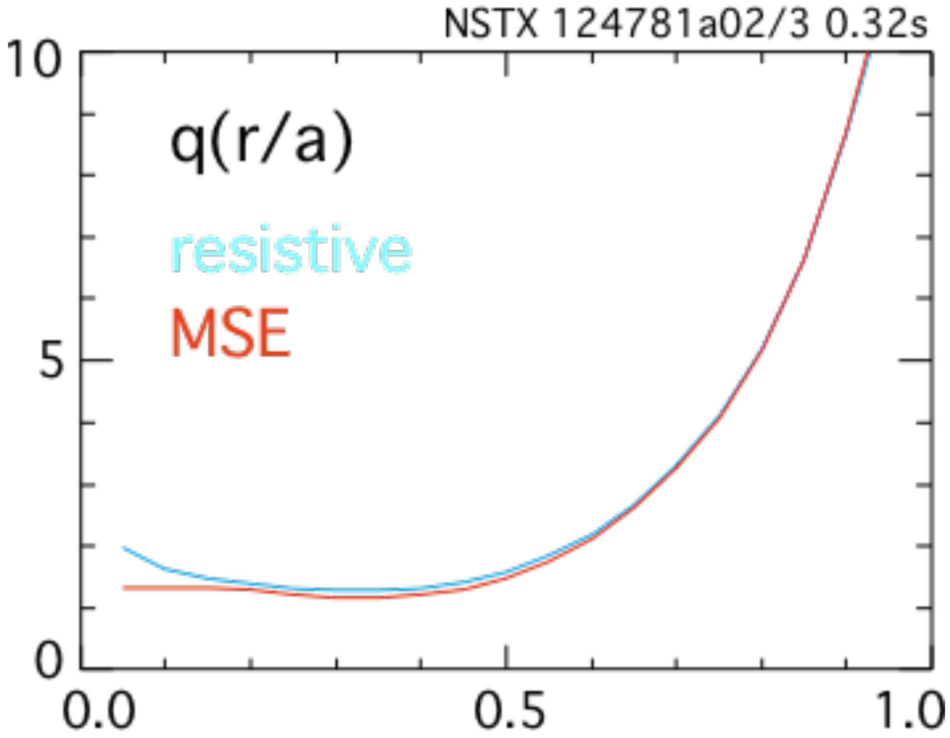


Figure 3 - Comparison of measured (MSE) and predicted (resistive) q profiles during TAE avalanche activity in NSTX. Differences in the core q profile may be due to TAE activity, but many additional sensitivity studies are needed before a definitive conclusion can be made.

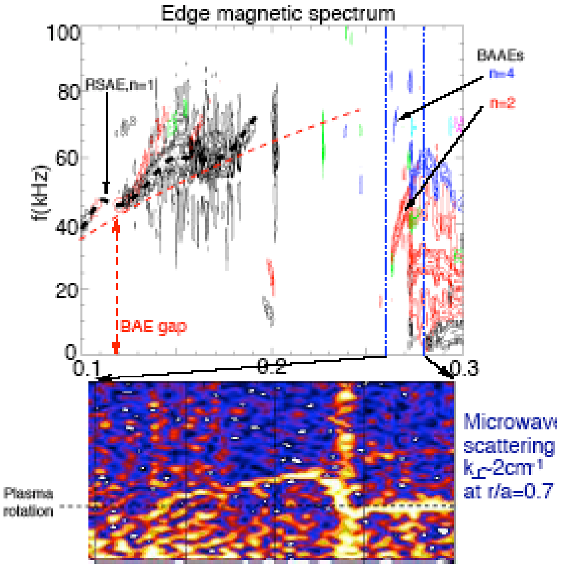


Figure 4 – Beta-induced Alfvén Eigenmodes

Beta-induced Alfvén-Acoustic Eigenmodes - New global MHD eigenmode solutions have been found numerically below the geodesic acoustic mode (GAM) frequency in gaps in the low frequency Alfvén - acoustic continuum. These new eigenmodes can explain observations of modes with frequencies well below the TAE frequency in NSTX (Fig. 4). These global eigenmodes, referred to here as Beta-induced Alfvén-Acoustic Eigenmodes (BAAE), exist in the low magnetic safety factor region near the extrema of the Alfvén-acoustic continuum. In accordance with the linear dispersion relation, the BAAE frequency increases as the safety factor, q, decreases. We show that BAAEs can be responsible for the observations of low frequency modes in relatively high beta > 20% NSTX plasmas. In contrast to the mostly electrostatic character of GAMs, the new global modes also contain an electromagnetic (magnetic field line bending) component due to the Alfvén coupling, leading to wave phase velocities along the field line that are large compared to the sonic speed. Initial measurements with the high-k scattering diagnostics have found evidence of mode conversion to short wavelength kinetic Alfvén waves as the BAAE enters the continuum. The ability to make these measurements will be valuable in the study of other Alfvén waves as well. Qualitative and quantitative agreement between theoretical predictions and observations are found (Fig. 5). The similar branch was also observed in JET tokamak. [Gorelenkov, et.al. Phys.Lett.A, 2007 in press, Gorelenkov, et.al, EPS07, invited talk]. One of the important applications of BAAE observations is the possibility of inferring safety factor values at the region of low shear. This form of MHD spectroscopy was validated by MSE measurements and application of the theory.

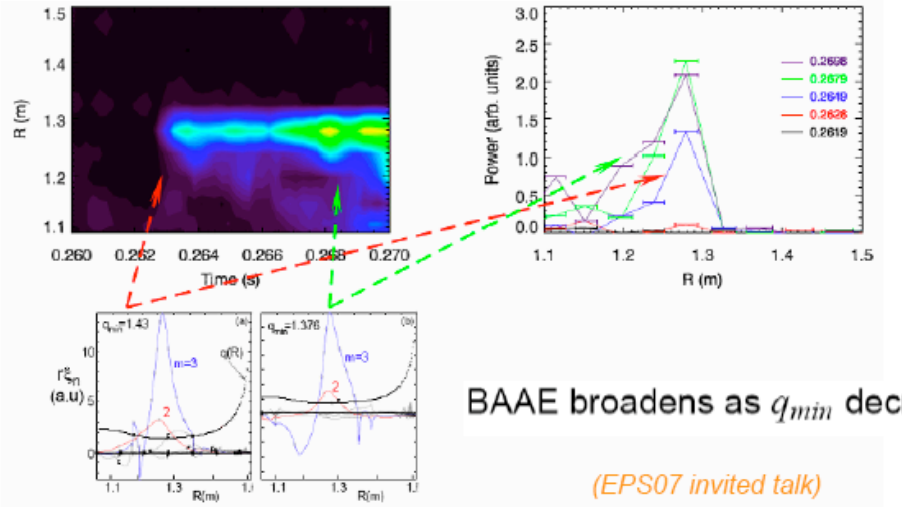


Figure 5 - Calcualted Nova-K ω and eigenfunction evolution is consistent with observation of Mirnov coils and USXR radial profile evolution (shown on the right figure).

Beta dependence of Alfvén Cascade Modes - Alfvén Cascade Modes (or reversed shear Alfven eigenmodes, RSAEs) have been found in low density, low β plasmas on the National Spherical Torus Experiment. An extension of the theory of Cascade modes which includes the coupling to Geodesic Acoustic Modes (GAM) is shown to imply their absence for typical spherical tokamak β (the ratio of thermal to magnetic energy). A scan in β in NSTX confirmed a threshold for suppression of Cascade modes in accord with theoretical predictions (Figure 6). Further, good agreement was found between the observed onset frequency and the frequency estimated from a simple dispersion relation for GAM. The time evolution of q_{min} as calculated from the observed mode frequency sweeping was also found to be in good agreement with that found from equilibrium reconstructions using measurement of the equilibrium magnetic field pitch. This measurement was made with a Motional Stark Effect (MSE) diagnostic. Some measurements have been made of the internal structure of these modes.

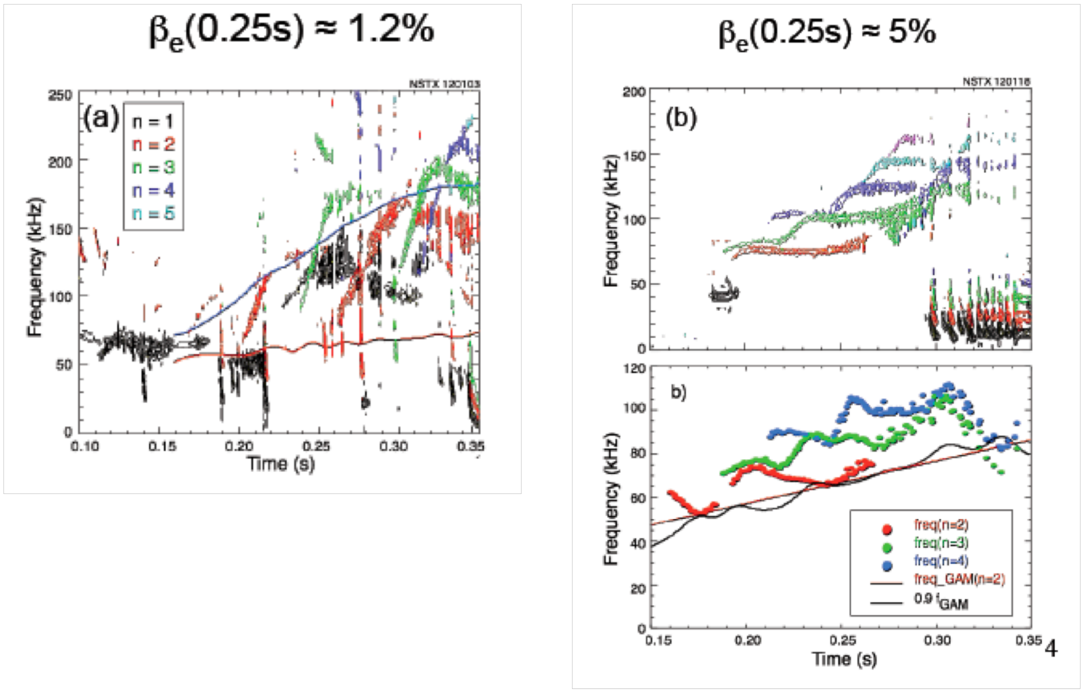


Figure 6 – The measured Alfven Cascades with plasma beta variation is consistent with recent theoretical models of Alfven Cascades mode-coupling to Geodestic Acoustic Modes.

Hole-Clump Pair - Neutral Beam Driven Compressional Alfvén Eigenmodes (CAE) at frequencies in the range $0.2\ \Omega_{ci} \leq \omega \leq \Omega_{ci}$ are commonly seen in NSTX plasmas. The modes typically have a spectrum with multiple frequency peaks, sometimes equally spaced and with sequential toroidal mode numbers. The modes are counter-propagating for moderate mode numbers, $3 \leq n \leq 6$, and co-propagating for high mode numbers $9 \leq n \leq 13$. The frequency has a scaling with toroidal field and plasma density consistent with Alfvén waves. The modes have been observed with high bandwidth magnetic pick-up coils and with a reflectometer. The high-k scattering system has again, in some instances, detected coherent modes with frequencies matching those seen on the Mirnov coils, suggesting continuum damping through mode-conversion to kinetic Alfvén waves. Alfvénic bursts (AB) of either compressional or global Alfvén eigenmodes, with strong frequency chirps have been observed in the early neutral beam-heating phase of discharges (Figure 7). The bursts last for < 0.3 – 0.7 ms, and the mode frequency chirps simultaneously up and down. The frequency evolution of the bursts is well described by the "Hole-clump pair" theory of Berk, Breizman, and Petviashvili. The AB arises from the generation of a hole in the particle distribution function, paired with a clump, and the non-linear interaction of the instability with the distribution function results in the propagation of the holes and clumps in phase space, which together with background damping, results in the simultaneous upward and downward frequency chirps of the mode. One of the most important results of hole-clump observation is the insight into the nature of wave-particle interaction. In the case of CAEs observed in NSTX one can expect long lived coherent structures in the fast particle phase space. In addition the hole-clump theory relates the rate of the frequency chirp to the linear damping rate of the mode. The damping rate determined by the frequency chirping is found to be in good agreement with predictions of the NOVA-k code.

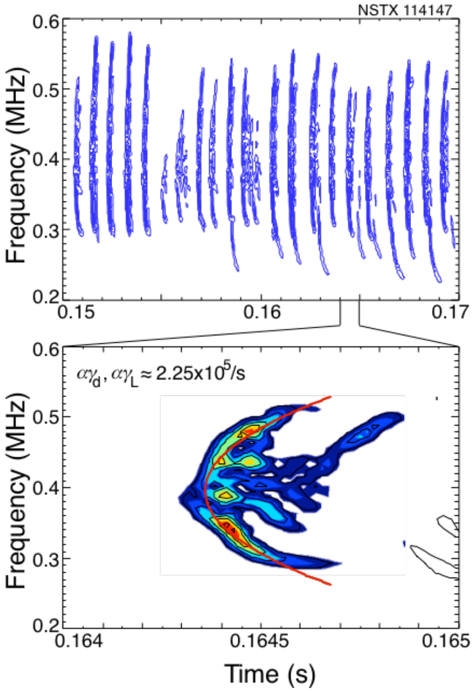


Figure 7 – CAE hole-clumps (Angelfish)