Suppression of energetic particle driven instabilities with HHFW heating

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Many methods, ranging from application of non-axisymmetric fields [1] to using RF heating to directly affect the fast ion distribution [2], have been proposed or observed to modify fast particle driven instabilities. Here we report on experiments where High Harmonic Fast Wave heating (HHFW) [3] was successful in completely suppressing not only the Toroidal Alfvén Eigenmodes (TAE), but also Global Alfvén Eigenmodes (GAE) and fishbone activity. What is particularly interesting about these experiments is that the TAE are excited through a broad range of resonances, the GAE through a Doppler-shifted cyclotron resonance and the fishbones through precession drift or bounce resonance, yet the HHFW simultaneously suppressed all of these instabilities.

In Fig. 1 are shown spectrograms from two similar NSTX shots, both with 2 MW of neutral beam heating from 0.15s to 0.6s. The first two panels of Fig. 1 compare spectrograms covering the GAE frequency range for shots, (a) with and, (b) without HHFW heating. GAE activity is seen shortly after beam injection starts for both shots, but is suppressed with HHFW heating. Spectrograms for the TAE and fishbone frequency ranges are shown in panels (c) and (d). Again, TAE are present for both shots prior to the HHFW heating, but both TAE and fishbones are suppressed by the HHFW. The GAE, TAE and fishbones reappear after HHFW heating as seen in panels (b) and (d).

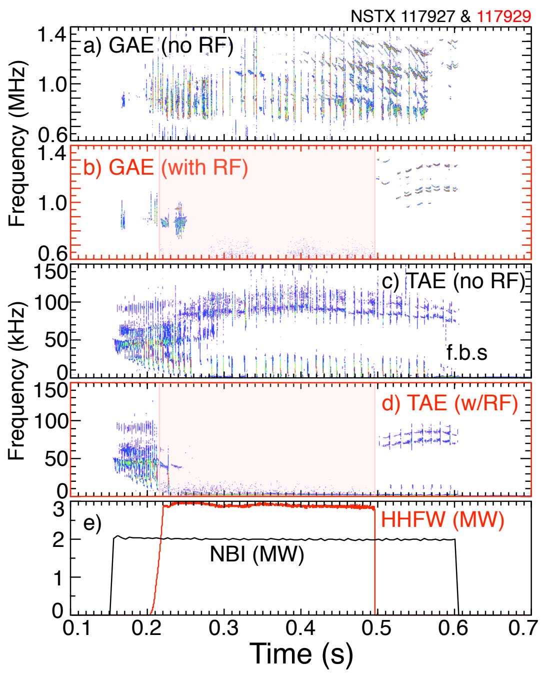

Fig. 1. Spectrograms showing GAE frequency range a) w/o RF, b) with RF, TAE frequency range c) w/o RF, d) with RF and e) NBI and HHFW power waveforms.

The threshold power for stabiliization is about 1.5 MW of HHFW for the 2MW of NBI used in these shots. In Figure 2 is shown a shot with 2 MW of NBI during which a 1.5 MW pulse of HHFW is applied. As can be seen in Fig. 2a, the TAE activity is reduced, but not suppressed during the HHFW pulse, and returns shortly after the end of HHFW heating. A counter-propagating n=1 kink mode appears shortly after HHFW heating onset and persists a few 10's of ms after.

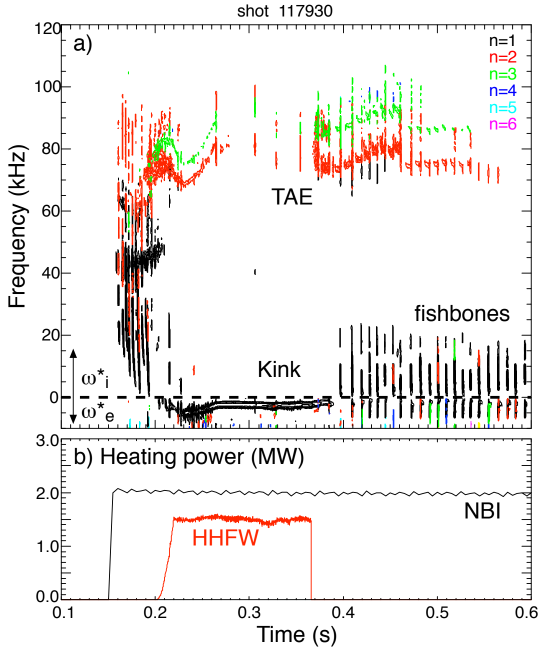

Fig. 2. Spectrogram showing partial suppression of TAE with 1.5 MW of HHFW power. TAE and fishbones recover after end of HHFW heating.

The timescales for mode suppression at HHFW onset, and for the modes to recover after HHFW heating could provide information on the mechanism of mode suppression. If we expand the spectrograms from Fig. 1 around the start of HHFW heating (Fig. 3), it is seen that both the GAE and TAE activity persist for 40 to 50 ms after the start of HHFW heating. The strong frequency chirping of both the TAE and GAE appear to be quickly suppressed, although in both cases, frequency chirps do reappear. An n=1, counter-propagating mode appears at about the same time the TAE and GAE are completely suppressed. The n=1 is commonly observed during HHFW heating, and often persists after HHFW heating ends (*c.f.,* Fig 2a). The TAE activity co-exists with the n=1 kink at lower power, as in Fig. 2a, so it is not believed that the n=1 is responsible for suppressing the TAE or GAE. The delay in suppression after start of HHFW heating then suggests that it either takes some time to modify the fast ion distribution responsible for exciting the TAE and GAE, or there was some change in the equilibrium plasma parameters during this interval which affected the stability of the Alfvénic modes.

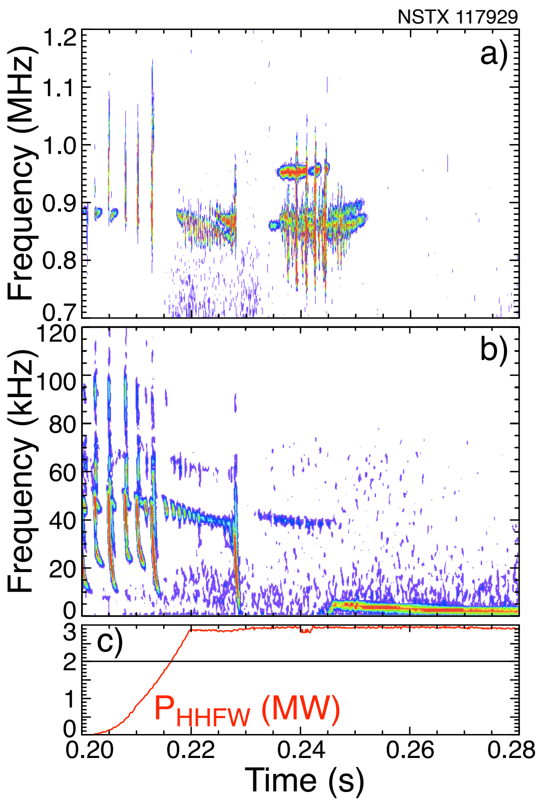

Fig. 3. a) spectrogram showing suppression of GAE with HHFW heating, b) spectrogram covering TAE frequency range, c) evolution of transmitted HHFW power.

Expanding the spectrograms about the end of HHFW heating, both TAE and GAE reappear within a few ms of the end of HHFW (Fig. 4). This is much shorter than the fast-ion slowing down time, indicating that the drive for these modes are the full-energy (or half or third energy) beam ions. The TAE appear to be avalanching, even shortly after their reappearance. The TAE avalanches are correlated with a weak fishbone-like mode. The reappearance of the TAE and GAE argue against an explanation that these discharges were evolving towards equilibrium conditions where the *AE were intrinsically stable.

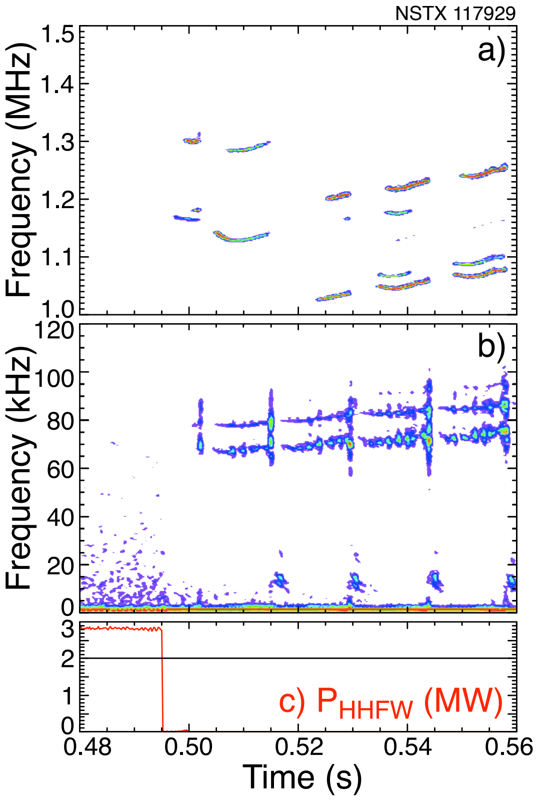

Fig. 4. a) spectrogram showing recovery of GAE after end HHFW heating, b) spectrogram covering TAE frequency range, c) evolution of transmitted HHFW power.

In this experiment there are fourteen shots with various combinations of HHFW and NBI heating. There is one shot with only 2MW of NBI heating (Figs. 1a and 1c), one shot with only 2 MW of HHFW heating (no beams). The other twelve shots all had 2MW of NBI with between 1.5 MW and 3 MW of HHFW heating. In Fig. 5 is shown the rms fluctuation levels for TAE and GAE activity against the average HHFW power (all shots here had 2 MW of NBI heating). The rms fluctuation level for points with HHFW power is averaged over the HHFW heating period, excluding the first 50 ms as suppression is typically delayed by up to 50 ms. The no-HHFW power points all follow the HHFW heating period. Initial beam heating periods before HHFW heating were excluded as the q-profile had typically not relaxed, and TAE activity was qualitatively different.

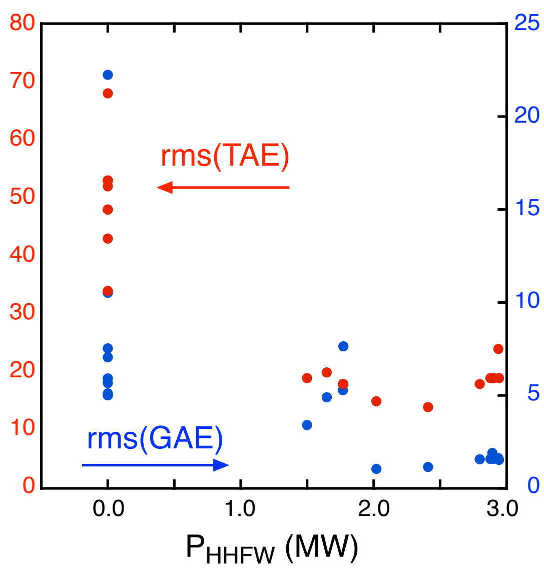

Fig. 5. rms fluctuation level 60 - 100 kHz (TAE) in red, 0.6 - 1.4 MHz (GAE) in blue *vs*. HHFW power.

A database was constructed of plasma parameters in each 25 ms interval of the plasmas in this experiment to look for correlations of thermal plasma parameters with TAE presence. In Fig. 6 are shown the average density and the q_{min} for each of the 25 ms intervals. The red points correspond to intervals where TAE were present with beams, but no HHFW heating. The green points are intervals where TAE were present with beam and HHFW heating, mostly time intervals just after the start of HHFW heating, or intervals with lower HHFW power (1.5 to 2 MW). Finally, the blue points are intervals where TAE activity is absent, despite 2 MW of NBI heating, presumably suppressed by the HHFW heating. The TAE-quiescent parameters of electron density, q_{min} (as well as electron temperature, not shown) overlap the parameter ranges for shots where TAE were present with only NBI heating.

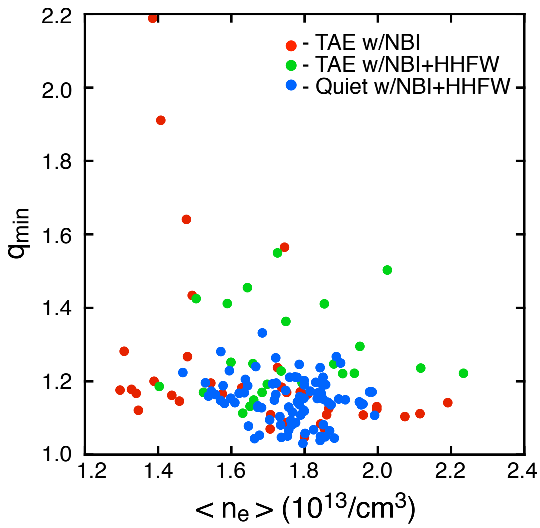

Fig. 6. Line averaged electron density and q_{min}, averaged over 25ms intervals from twelve discharges. Red points are conditions with TAE and NBI, but no HHFW, green TAE with NBI and HHFW, blue are quiet with NBI and HHFW.

HHFW heating is found to simultaneously suppress fishbones, TAE and GAE. Fishbones are excited through precession drift resonance, GAE through Doppler-shifted cyclotron resonance and TAE through broad range of resonances. This result has only been reproducibly seen in 300 kA, He target plasmas heated with 2 MW of NBI. There are fourteen shots in this experiment, one with NBI-only, one with HHFW-only and twelve with NBI + 1.5 to 3 MW of HHFW. More than 2MW of HHFW completely stabilized fast-ion driven modes, and less than 2 MW could reduce mode amplitudes.

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