Intricate Interplay of Super-Energetic Particles and Plasma Waves

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Energetic ions are commonly present in astrophysical plasmas as well as in certain laboratory plasmas. In a burning deuterium-tritium fusion plasma, nuclear fusion reactions produce energetic (3.5-MeV) alpha particles. In astrophysics, high-energy particles are prominently observed in solar flares and cosmic rays. Both in laboratory and space plasmas, high-energy particles can often lose or gain energy very rapidly without simple explanation. As observed in recent experiments on the National Spherical Torus Experiment (NSTX), the rather intricate interplay between energetic particles and excited plasma waves plays a profound role.

With a special neutralized ion-beam injection system, it is possible to inject ions into the NSTX plasma at speeds up to 3×10^8 cm/s with power of up to 8 million watts, enabling the investigation of the wave-particle interactions deep into the so-called super-Alfvénic regime. Alfvén waves are very common in magnetized plasmas both in space and laboratory, much like the sound waves in everyday life. Alfvén waves can be easily excited by any disturbance of the magnetic field line (like plucking a rubber band or a spring.) Just as the characteristics of sound waves change as an airplane passes through the sound barrier into the super-sonic regime, the physics of wave-particle interactions in hot plasmas can change dramatically as the energetic particle velocity passes through the Alfvén wave velocity, going “super-Alfvénic”.

On NSTX, a rich variety of high frequency plasma waves can be excited. In Figure 1, a typical time evolution of the excited wave frequency spectra is shown. The Figure shows Toroidal Alfvén Eigen-modes (TAEs) that are excited in the 100-kHz range. TAEs are naturally occurring Alfvén waves made unstable by the energetic ions. At lower frequency range between 10 and 100 kHz, we see EPMs or Energetic Particle Modes. The EPMs are energetic-ion driven modes that exist only because of the presence of energetic ions. In addition, we also see a group of very high frequency modes called CAE (Compressional Alfvén Eigen-modes) in the MHz range. The Figure shows very strong “chirping” (a rapid frequency drop in time) for both TAEs and EPMs. This frequency chirping behavior is attributed to the strong wave-particle interactions. The corresponding fusion neutron emission evolution is shown in the lower trace of Figure 1. The neutron is a result of fusion reaction mainly between the energetic deuterium ions with the background ions. One can see occasional rapid drops in neutron emission associated with the chirping behavior, as seen in Figure 1. The rapid drop in fusion neutron emission is indicative of a rapid decrease in energy or an expulsion of energetic ions from the plasma core.

In a reactor, TAEs and EPMs could reduce fusion power output, and the impinging energetic ions expelled by chirping modes could damage the reactor’s chambers walls. Consequently, it would be beneficial for a fusion reactor to stabilize such Alfvénic and other plasma wave instabilities and prevent sudden losses of energetic ions from the fusion plasma core. Recently in NSTX, the stabilization of TAE-like modes by the application of radiofrequency (rf) waves (High Harmonic Fast Waves) was demonstrated. The rf waves accelerate plasma ions in a direction perpendicular to the local magnetic field line, and the resulting change in their energetic particle velocity distribution stabilizes TAE-like modes completely (see Figure 2).

The super-Alfvénic wave-particle interaction is an intriguing but complex area of research. Understanding these processes could lead to a better fusion reactor design, as well as unlocking some of the mysteries of the origin of the solar and cosmic rays.

Ref: E.E. Ruskov et al., PP1.007 at APS

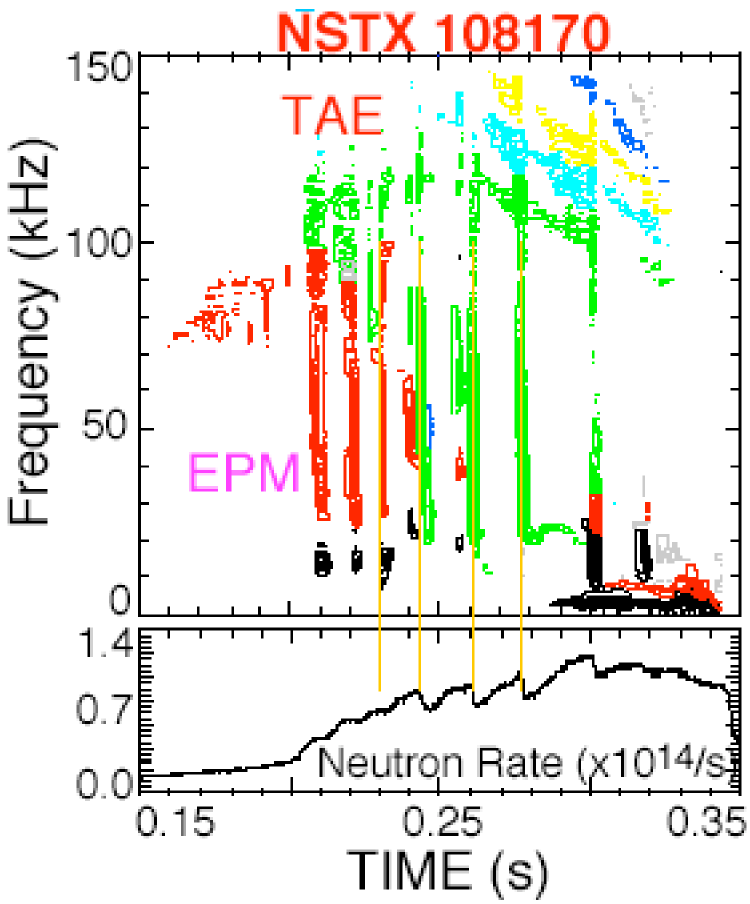

Fig. 1. A time trace of the frequency spectra of observed unstable plasma modes (TAEs and EPMs) due to the presence of super-Alfvenic high-energy ions. The bursting and chirping behavior can be seen for both TAEs and EPMs. The lower time trace shows the associated neutron drop indicative of the sudden loss of energetic ions from the reacting core.

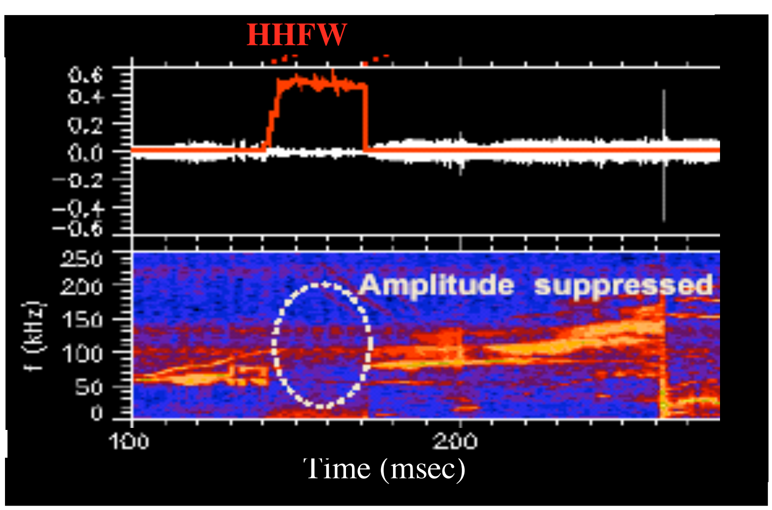

Fig. 2. A demonstration of stabilization of super-Alfvenic energetic particle driven instabilities by direct perpendicular acceleration of energetic ions by rf (HHFW) heating.