A Nonlinear Wrinkle in the Investigation of Fusion Plasma Heating by Fast Ions[†]

Novel observation of nonlinear plasma wave interactions motivates new thought on plasma heating by fast ions resulting from fusion reactions.

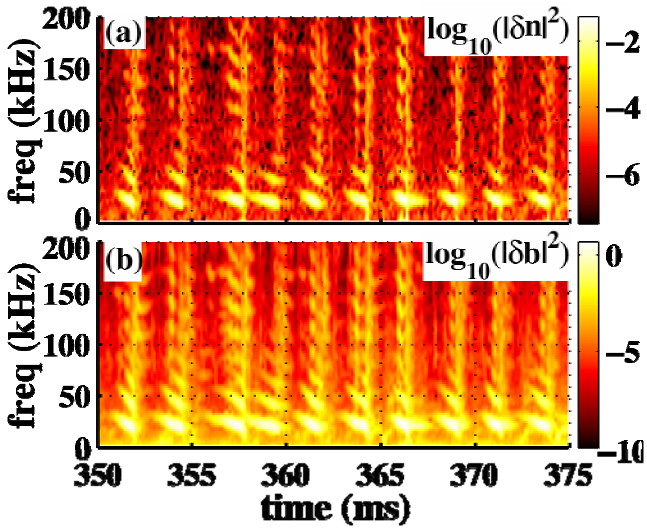

Figure 1: Time-dependent spectra of fluctuations in (a) core plasma density and (b) external plasma magnetic field. Simultaneous bursts in both indicate fast ion modes, which perturb entire plasma. Peaks at multiple frequencies in each burst are different modes. Modes above 85 kHz are "TAE" modes, while those below are "EPM" modes.*

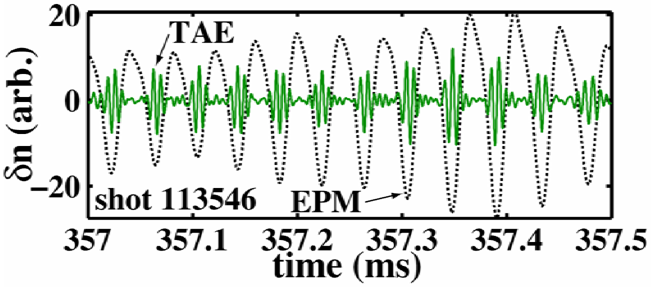

Figure 2: Dashed and solid lines show core plasma density perturbations due to fast ion modes as they propagate repeatedly around torus. Dashed line is large wavelength mode ("EPM" mode). Solid line is sum of multiple short wavelength modes ("TAE" modes) that propagate in lockstep because of their collective nonlinear interactions with the EPM. The sum of TAE modes forms a "wave-packet" that is seen as a pulse every time it passes the measurement system.

A critical element in understanding and controlling future burning plasmas such as ITER is a reliable model of how fusion reactions heat the plasma and thereby sustain the burn. It is well established that alpha particles (energetic Helium ions) produced by fusion reactions carry the energy that will heat burning plasma. However, exactly how alphas will deposit their energy is still an open question. One promising theory is that the alphas will excite several varieties of plasma waves—collectively known as fast ion modes (Fig. 1)—that will heat the plasma as they are damped. A factor that complicates this theory is the influence of the modes themselves on alpha trajectories. The modes include electromagnetic fields that can alter the trajectories. Consequently, they can affect the distribution of alphas in the plasma. They can even cause alphas that should be magnetically confined to escape without fully depositing their energy, making sustainment of the burn more challenging.

To address these issues, fast ion modes are currently investigated in non-burning "advanced fusion research" devices such as the National Spherical Torus Experiment (NSTX), where techniques used to heat the plasma—energetic particle beams and high power radio waves—often create fast ions similar in key ways to the alphas. For instance, the fast ions in NSTX and the fusion alphas have approximately the same Alfvénic Mach speed, or speed relative to the Alfvén velocity. The Alfvén velocity is a characteristic speed for the propagation of many varieties of fast ion mode. It is analogous to the speed of sound for sound waves. Generally speaking, the speed of an energetic ion relative to a wave is a significant factor in the wave-ion interaction.

In the course of recent research at NSTX, a phenomenon known as nonlinear three-wave interaction has, for the first time, been identified as playing a significant role in the way fast ion modes evolve in time and space in fusion plasmas. In rough terms, three-wave interaction is the driving of a wave by the joint action of two other waves. It is a well-known factor in the wave dynamics of many media. Three-wave interactions can, in principle, have many possible consequences for fast ion modes and their subsequent interaction with the fast ions that excited them. One important consequence demonstrated by these recent observations is the organization of many short wavelength fast ion modes into a spatially concentrated “wave-packet” (Fig. 2). This is enforced by their collective interactions with a much longer wavelength fast ion mode of a different type. By forming the wave-packet, the short wavelength modes may be expected to have a different effect on fast ion trajectories than they would if disorganized. This work will be reported by Neal Crocker et al. in Poster QP1.00011 at the 48th Annual Meeting of the Division of Plasma Physics, October 30–November 3 2006 in Philadelphia, PA.

This demonstration of three-wave interactions motivates interesting directions for future research. In the near term, the consequences of the observed wave-packet formation for fast ion trajectories must be investigated. Beyond that, much exciting research remains to be done, since even a cursory search yields abundant evidence of three-wave interactions among many other types fast ion modes in NSTX. There are, of course, many ways that this research can impact the understanding of the role of fast ion modes in burning plasmas. For instance, a well-known universal effect of three-wave interactions is to increase the complexity of a wave spectrum. Waves excited by some energy source (e.g. alphas in ITER) can spend energy exciting other waves, which can subsequently excite yet others, and so on, in a sort of chain reaction. Complexity of this sort has potential negative and positive consequences for devices such as ITER, where the burn is sustained by the deposition of alpha energy. On the positive side, it can enhance the efficiency with which alphas deposit their energy because the indirectly excited modes may include some that are much more strongly damped than the modes directly excited by the alphas. On the negative side, this complexity can potentially cause alphas to undergo random walks that take them out of the plasma at a much greater rate than would result from trajectory alteration caused by the few directly excited fast ion modes. Both of these possibilities will be investigated in NSTX research.

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