A Nonlinear Wrinkle in the Investigation of Heating of Fusion Plasmas by Fast Ions†

Nonlinear interactions of plasma waves excited by fast ions in fusion research plasmas conclusively demonstrated for the first time.

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. A leading candidate is the excitation of several varieties of plasma waves—collectively known as fast ion modes (Fig. 1) —that heat the plasma as they are damped. This process is complicated by the influence of the modes themselves on alpha trajectories. The modes can alter the magnetically confined trajectories, redistributing alphas in the plasma. They can even cause alphas to escape without fully depositing their energy, making sustainment of the burn more challenging.

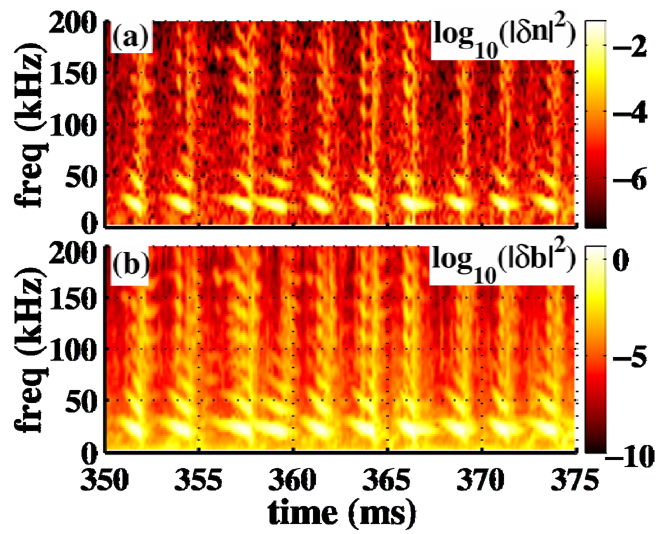

Figure 1: Time-dependent spectra of fluctuations in (a) core plasma density and (b) external plasma magnetic field. Simultaneous bursts in both indicate fast ion modes, which perturb entire plasma. Peaks at multiple frequencies in each burst are different modes. Modes above 85 kHz are "TAE" modes, while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

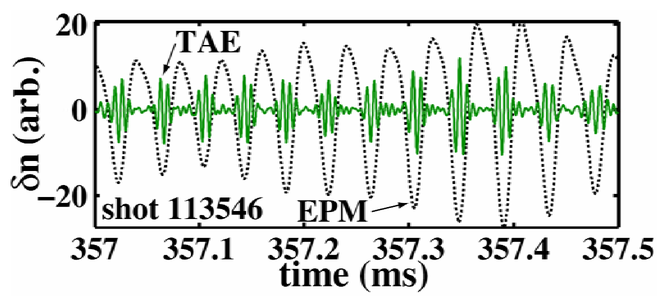

Figure 2: Dashed and solid lines show core plasma density perturbations due to fast ion modes as they propagate repeatedly around torus. Dashed line is large wavelength mode ("EPM" mode). Solid line is sum of multiple short wavelength modes ("TAE" modes) that propagate in lockstep because of their collective 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.

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. Generally speaking, the speed of an energetic ion relative to a wave is, of course, a significant factor in the wave-ion interaction.

In the course of research at NSTX, a phenomenon known as nonlinear three-wave interaction has recently, 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.

These results open up interesting avenues for future research. For instance, the nature of the effect of the wave-packet on fast ion trajectories is an interesting question. Additionally, evidence of three-wave interactions among many other types fast ion modes in NSTX is abundant, so much exciting research remains to be done exploring the consequences of their interactions. For instance, one effect that may be addressed is of particular relevance to ITER. A well-known universal effect of three wave interactions is to increase the complexity of the wave spectrum in a medium. Waves excited by some energy source such as 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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