New Wave Effects in Compressing Plasma

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***Abstract*—A new mechanism is predicted whereby waves in compressing plasma first grow and then abruptly transfer energy to particles or fields.**

***Index Terms*—Kinetic theory, plasma simulation, plasma waves.**

WHEN plasmas undergo densification through compression or ionization, embedded waves are affected. For compression that is slow compared to the wave frequency, but fast compared to collision frequencies, waves gain energy while conserving wave action. The action conservation is a fundamental constraint on densifying or rarefying plasma that has important implications to both laboratory and astrophysical plasmas [1], [2].

In fact, very new kinds of phenomena can be predicted to occur in densifying plasma through embedded plasma waves. As but one example, waves might accumulate energy and then dump it abruptly and collisionlessly on particular species at a predetermined moment of time, thereby manipulating selectively the tail of the velocity distribution [3]. As a result of this effect, there could be sudden particle heating leading to increased fusion events or sudden current and magnetic field generation leading to enhanced confinement or resistivity. Since the energy for these effects is derived from the compression, the effect can be large.

Fig. 1 shows the results of a particle-in-cell (PIC) simulation illustrating this effect in plasma undergoing compression. To simulate these effects, the plasma, together with its initially embedded plasma wave, evolves through a one-dimensional (1-D) electrostatic PIC code in a 1-D box with reflecting boundary conditions. To produce the compression, the right wall of the box approaches the fixed left wall at a constant velocity, so that the length of the box $L(t)$ varies with time. Particles cannot leave the box, so total charge neutrality is maintained. Only electrostatic standing waves with integer wavenumbers $m = kL/2\pi$ can be excited. The electrons were initialized randomly as Maxwellian, and to produce the figure, ions were modeled as a charge-neutralizing homogeneous background. (As a check, simulating the ion motion does not change qualitatively the picture offered here [3].)

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An analysis of the simulation shows that the wave action is indeed conserved in the PIC simulations, confirming the general theory of adiabatic wave compression, at least until the wave is suddenly Landau damped on the electrons. Because of the action conservation, the wave amplitude grows with compression, meaning that some of the mechanical work of the slowly moving wall is channeled into coherent motion of the particles. The sudden damping occurs because, under compression parallel to the wavenumber, the electron temperature increases, while the plasma wave phase velocity decreases (the wavenumber increases faster than the frequency). Eventually, the wave phase velocity intersects with the tail particles of the electron distribution, leading to the very abrupt damping of the wave. What Fig. 1 shows is the characteristic signature of the sudden damping. Note that the tails of the electron distribution function form a wing shape as a result of the damping. However, after the wave has damped completely, further compression leaves the wing shape intact since all electrons simply increase their velocity proportionately. Hence, even after the wave is damped, the final distribution function reflects the presence and the characteristics of the initially embedded wave.

Fig. 1 illustrates the sudden heating due to an embedded wave. The heating occurs in a switchlike manner at a predetermined moment in time, when the Landau damping condition is met. It may be possible to have sudden magnetic field generation due to an embedded wave as well. To generate magnetic fields, the tails formed should be asymmetric, rather than forced to be symmetric as they are here by hard-wall boundary conditions. However, for a traveling wave, with compression/expansion in a direction perpendicular to the wave, an asymmetric tail could form, and it would do so similarly abruptly. Thus, a current-drive effect could be produced at a predetermined time also in a switchlike manner, through any of the wave-induced current-drive mechanisms available in stationary plasma [4].

Although the simulation reported here is just a thought experiment at present, this *switch* paradigm might be useful in connection with the current groundbreaking high energy density experiments, such as those at National Ignition Facility and Z-Machine, where substantial investments are being made in the extreme compression of plasma. These *built-in switches* might then trigger at just the correct moment within the plasma compression history the very abrupt release of wave energy and the associated abrupt plasma heating, which might select just one species of plasma within one region of resonant velocity space. The extraordinary but admittedly highly speculative result could be then, in principle, the very sudden generation of heat or electric current and associated magnetic fields at a predetermined instant of time.

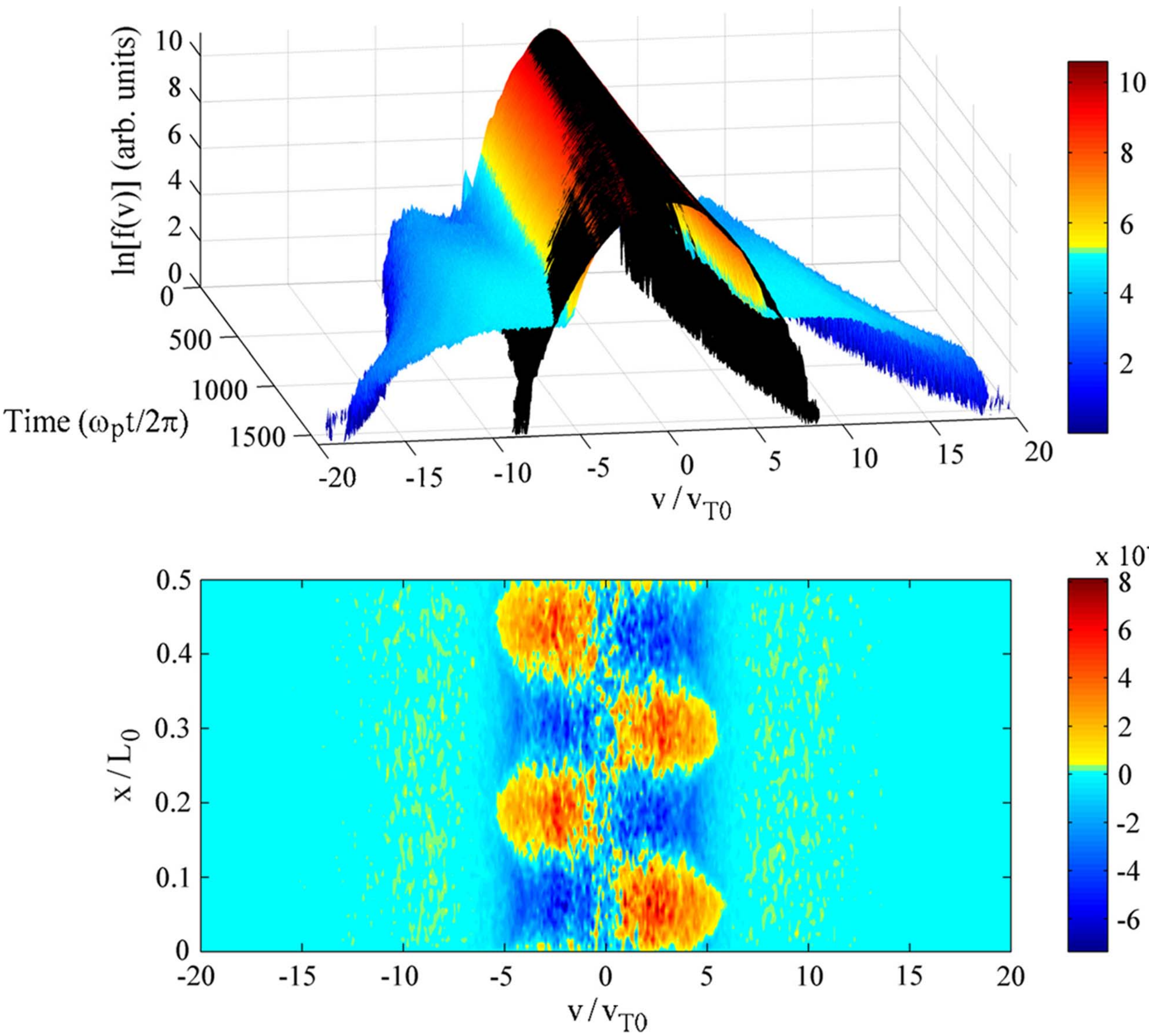

Fig. 1. PIC numerical simulation of compressed Langmuir wave. (Top) Signature of abrupt damping of Langmuir wave, forming characteristic velocity tails in the space-averaged electron distribution function. (Blue color) The velocity tails are overlaid against the distribution function of similar compressing plasma in (black color) the absence of embedded Langmuir wave. Note that, in time, the initially small tail becomes more pronounced and eventually adopts a self-similar shape in velocity space once the wave has damped away completely. (Bottom) Phase space density difference between initially similar distributions, one with a Langmuir wave and one without, at advanced compression state. Suprathermal electron tails are observed near $\pm 10 v_{T0}$, while the remnants of a parasitic second mode that has not yet damped are also seen, unlike the primary wave that was most intense initially.

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