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ULTRA-STRONG LANGMUIR TURBULENCE

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ABSTRACT

Langmuir collapse has been shown to be an important effect in a number of experimental venues including laser-plasma interactions. We explore "Ultra-Strong Langmuir Turbulence" by numerical simulation of full two-fluid plasma theory. Long-time simulations demonstrate the onset of the modulational instability, the formation of solitons and their subsequent collapse, followed by burn-out and 'nucleation events'. Even relatively weak initial amplitudes may eventually lead to large density depletions (over 50%) and very intense collapse events ($|E|^2/4\pi nT >> 1$). The onset of wavebreaking is also indicated. Comparisons with the Zakharov model demonstrate its validity for early times and its eventual failure for long times. Applications of these results are discussed.

Strong Langmuir turbulence may be characterized in one dimension by the formation of Langmuir solitons (nonlinear self-localized regions of enhanced electric field in associated density depressions). However, solitons are unstable to catastrophic collapse in multi-dimensional systems[1]. As solitons collapse their spatial extent tends toward zero and the associated electric field in the soliton becomes extremely large. The collapse proceeds until the spatial extent of the soliton is only a few Debye lengths when strong wave-particle interactions dominate, and the energy in the trapped electric field is deposited in a population of now suprathermal electrons, in a process known as 'burn-out'[2,3]. This phenomena of Langmuir collapse is therefore, a copious source of "hot electrons" deleterious to laser fusion target performance.

Intense Langmuir waves, produced in the corona of laser fusion targets by a number of instabilities, have long been recognized as a critical factor in determining target behavior and performance. Recent laser-plasma experiments[4] confirm the importance of interactions between Langmuir waves from stimulated Raman scatter (SRS) and the ion acoustic waves from stimulated Brillouin scatter (SBS) in controlling the evolution of these instabilities in the corona. Virtually all of the theoretical descriptions[1-5] of the evolution of intense Langmuir waves interacting with ion density perturbations, (i.e. strong Langmuir turbulence), can be cast in the form put forth by Zakharov[1] more than fifteen years ago:

$$i\partial_t E + \partial_x^2 E = nE \tag{1}$$

$$\partial_t^2 n - \partial_x^2 n = \partial_x^2 |E|^2 \tag{2}$$

where E is the electric field of the envelope of the Langmuir wave and n is the ion density perturbation. These equations (the so-called "Zakharov equations") describe the coupling of Langmuir waves to ion density perturbations and the evolution of ion density perturbations acted upon by the ponderomotive force associated with the Langmuir waves. The behavior of the turbulence predicted by these equations is characterized by the formation of Langmuir solitons (nonlinear self-localized regions of enhanced electric field in associated density depressions). The solitons are unstable to catastrophic collapse in multidimensional systems. As the solitons collapse their spatial extent tends toward zero and the associated electric field in the soliton becomes extremely intense. This collapse proceeds until the spatial extent of the soliton is only a few Debye lengths when strong wave-particle interactions dominate. At this point the energy in the trapped electric field is deposited in a population of now suprathermal electrons. Hence, this phenomena of Langmuir collapse is a source of copious production of hot electrons deleterious to target performance. This process is called 'burn-out'.[3] What remains of the remnant soliton is an ion density hole which can trap a pump field if present, thus acting as site for a new soliton to form, a process called 'nucleation'.

The Zakharov model (Eqs. 1 and 2) and those models derived from it[5] incorporates several assumptions which limit its application to high intensities: low frequency charge quasi-neutrality, low wave intensity relative to thermal pressure, small density perturbations, and separation of time-scales (i.e. the electric field envelope evolves much more slowly than the high frequency electron plasma oscillations). Yet the occurrence of the phenomena predicted by these models at small but finite amplitudes, localization and subsequent collapse, point to the breakdown of these same assumptions in the regime of interest. We have therefore proposed[6-11] the use of full two-fluid plasma theory as a model for "ultra-strong Langmuir turbulence":

$$\partial_t n_e + \nabla \cdot (n_e \mathbf{v}_e) = 0 \tag{3}$$

$$\partial_t \mathbf{v}_e + \mathbf{v}_e \cdot \nabla \mathbf{v}_e = -\frac{1}{n_e m_e} \nabla p_e - \frac{e}{m_e} \mathbf{E} - \frac{e}{m_e} \mathbf{E}_0 - \nu_e \mathbf{v}_e \tag{4}$$

$$\partial_t n_i + \nabla \cdot (n_i \mathbf{v}_i) = 0 \tag{5}$$

$$\partial_t \mathbf{v}_i + \mathbf{v}_i \cdot \nabla \mathbf{v}_i = -\frac{1}{n_i m_i} \nabla p_i + \frac{e}{m_i} \mathbf{E} + \frac{e}{m_i} \mathbf{E}_0 - \nu_i \mathbf{v}_i \tag{6}$$

$$\nabla \cdot \mathbf{E} = 4\pi e (n_i - n_e) \tag{7}$$

$$\nabla p_e = \gamma_e T_e \nabla n_e \tag{8}$$

$$\nabla p_i = \gamma_i T_i \nabla n_i \tag{9}$$

where subscripts (e,i) denote variables of the electron and ion fluids respectively. Here, for the first time, we include new terms in Eqs. 4 and 6, to model the inclusion of a prescribed pump and damping mechanisms. This model contains none of the assumptions required to obtain the reduced Zakharov model and therefore is free from its inherent limitations. In its latest form, our model easily describes ultra-strong Langmuir turbulence in open systems as is more appropriate to actual experimental conditions.

We have previously designed and implemented a new computer code (ESHYDRO) to solve Eqs. (3-9) for the evolution of electric fields and densities describing ultra-strong Langmuir turbulence.[7-11] ESHYDRO has recently been modified to accommodate prescribed drivers and damping mechanisms appropriate to actual experimental conditions. Most importantly, our simulations confirm the modulational instability of two-fluid theory as predicted in our previous work[7-11] and demonstrated in Fig. 1 through Fig. 4. Figure 1 shows typical initial conditions. An electric field of value 0.4 (in natural electrostatic plasma units, $T_e/e\lambda_D$) is applied in a uniform plasma. Small random fluctuations imposed about this value give rise to the intensity pattern shown. In addition, small random fluctuations are added to the electron density n_e about its normalized ambient value of unity. The ion density (not shown) however, is initialized at its normalized value of unity without noise fluctuations. Figure 2 demonstrates the early onset of the modulational instability as evidenced by small ion density depressions appearing in the trace of Δn_i. In Fig. 3, the formation of solitons, characterized by the localization of electric field spikes in ion density holes, is quite evident by t=600 ω_{pe}^{-1} (electron plasma periods). The similarities of results from ESHYDRO to results previously obtained for the driven-damped Zakharov system[12,13] (Fig. 4) are striking. At low intensities the predictions of the Zakharov model are confirmed.

Figure 5 shows an ensemble of solitons fully developed. Note most of the intensities approach or exceed unity. This level of turbulence is far in excess of that accessible by the Zakharov de-

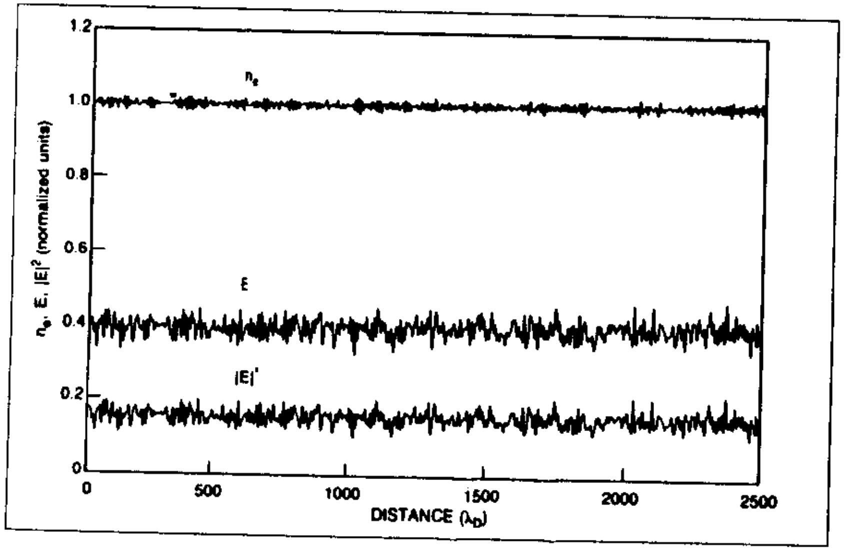

Fig. 1. Electron density, n_e, electric field, E, and intensity, $|E|^2$, as a function of distance (in Debye lengths) normalized to natural electrostatic plasma units (see text).

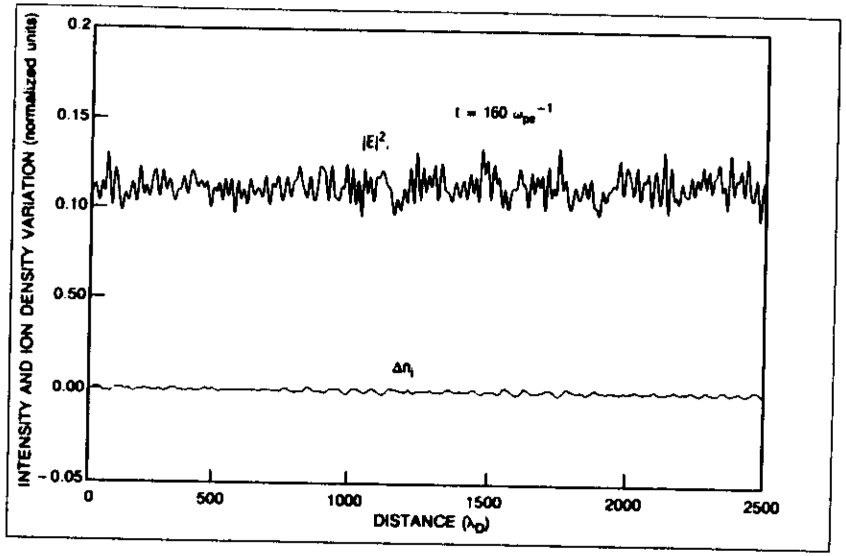

Fig. 2. Intensity and ion density variation in space at t=160 plasma periods. Note onset of modulational instability and the formation of ion density depletions

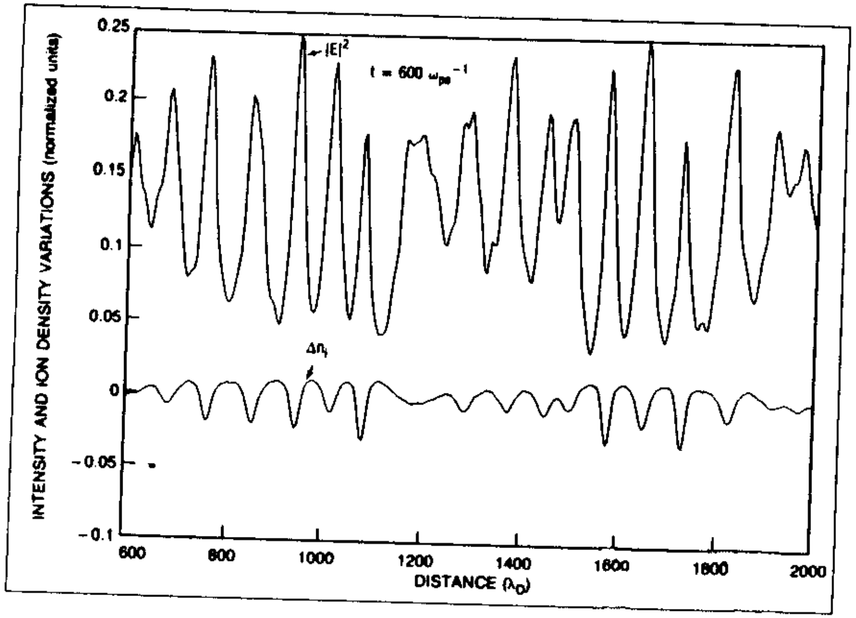

Fig. 3. Same as Fig. 2, for t=600 plasma periods. Note soliton formation.

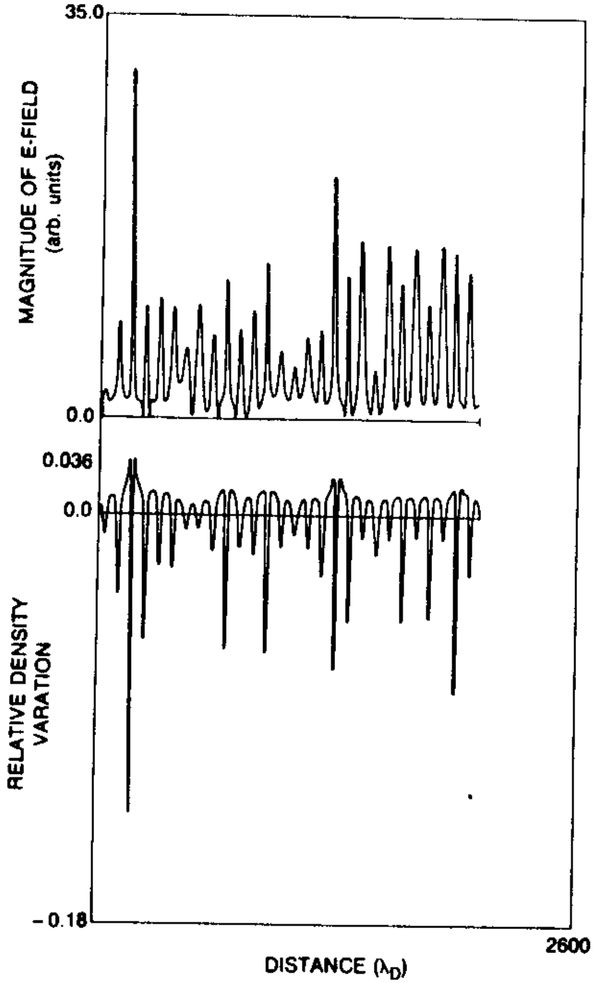

Fig. 4. Electric field and ion density variation in space from simulations of driven-damped Zakharov code[13] exhibit the same qualitative behavior as in Fig. 3.

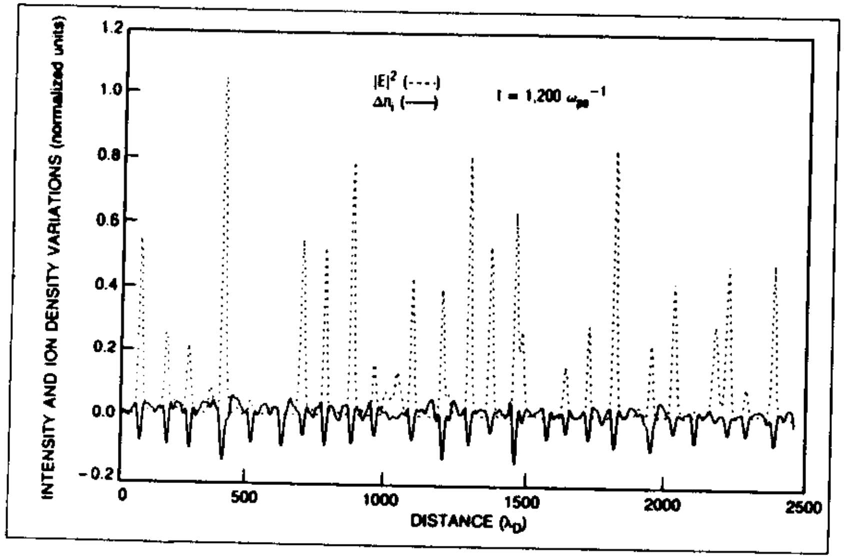

Fig. 5. Same as Fig. 2, for t=1200 plasma periods.

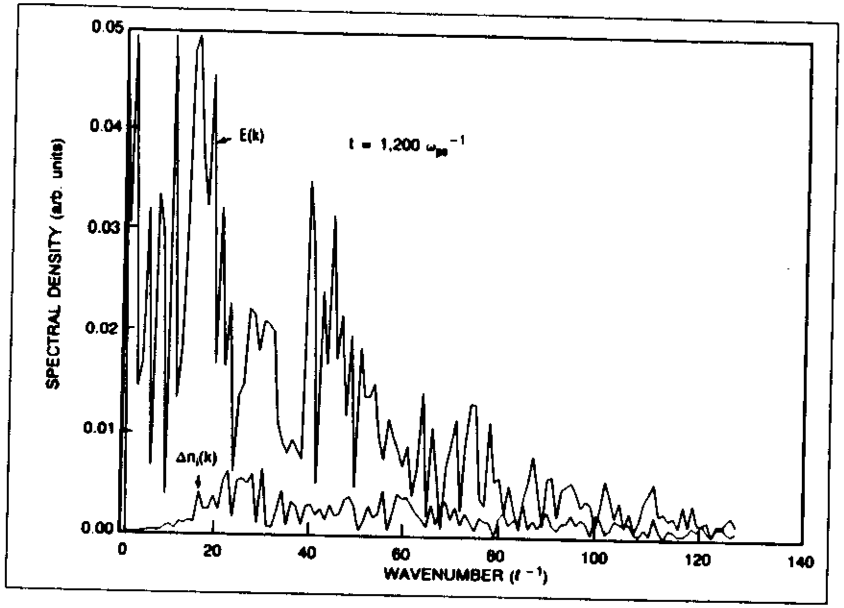

Fig. 6. Spectral densities of electric field and ion density as a function of wavenumber k, (measured in units of l^{-1}, where l is the number of periods in the system).

scriptions. Ion density holes at this time are approaching 20% depletions. Due to the split-step spectral method in use, Landau damping is conveniently included in the electron damping term. The consequence of this is already evident in a number of examples of soliton 'burn-out', ion density holes with little or no supporting electric field structure. Figure 6 shows the spectral densities of the electric field and ion density to be quite similar to those of the driven-damped Zakharov system.[13]

Figures 7 and 8 show continued evolution and saturation of the modulational instability. Note the individual solitons continue to increase in intensity until most remaining solitons have intensity values well in excess of unity. At this point, the damping mechanism saturates further growth and many examples of burn-out are evident. Note also, the ever-decreasing number of spikes. There are however, many examples of solitons being 'reborn', i.e. 'nucleation'. Figures 9 and 10 are blow-ups of the results in Figs. 7 and 8, to better illustrate this effect. These processes of cyclical burn-out, nucleation, and collapse, characterize the steady-state long-time evolution of the driven-damped two-fluid theory as demonstrated in Fig. 11 for t= 14,400 plasma periods. There are still fewer spikes at the saturated intensity. Note however, the number of density holes approaching 50% local evacuation of the plasmas density! These solutions are far beyond the reach of Zakharov-type models. They are, however, easily handled by our ultra-strong model which includes charge separation effects (see Fig. 12).

When driven at higher intensities, simulations of the full two-fluid theory indicate the onset of wavebreaking and harmonic generation, effects which are lost in Zakharov descriptions, but are important processes in competition with collapse. Because ESHYDRO solves specifically for the electron and ion velocities (e.g. Fig. 13), the onset of these effects is easily detected. Description of the evolution past the onset of wavebreaking awaits the results of work in progress.

Our current investigations extend this work in several important directions. Among these are: the exploration of phenomenological

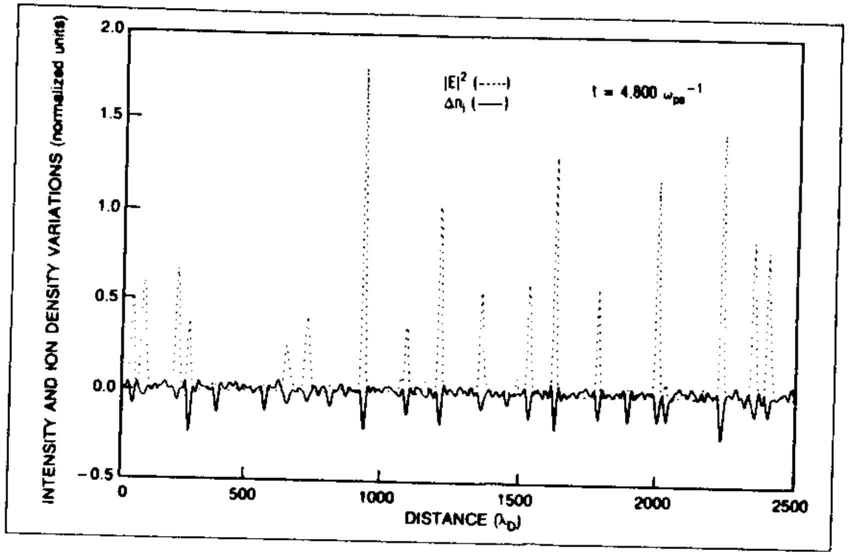

Fig. 7. Same as Fig. 2, for t=4800 plasma periods.

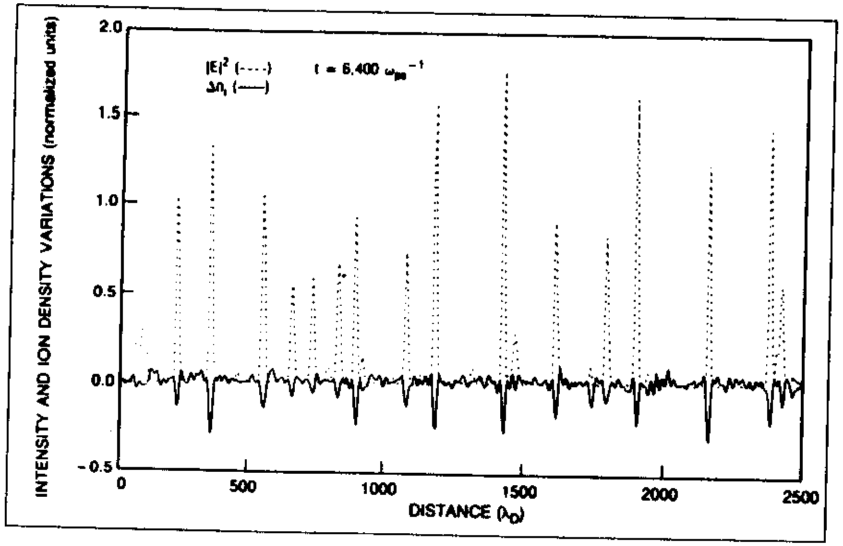

Fig. 8. Same as Fig. 2, for t=6400 plasma periods.

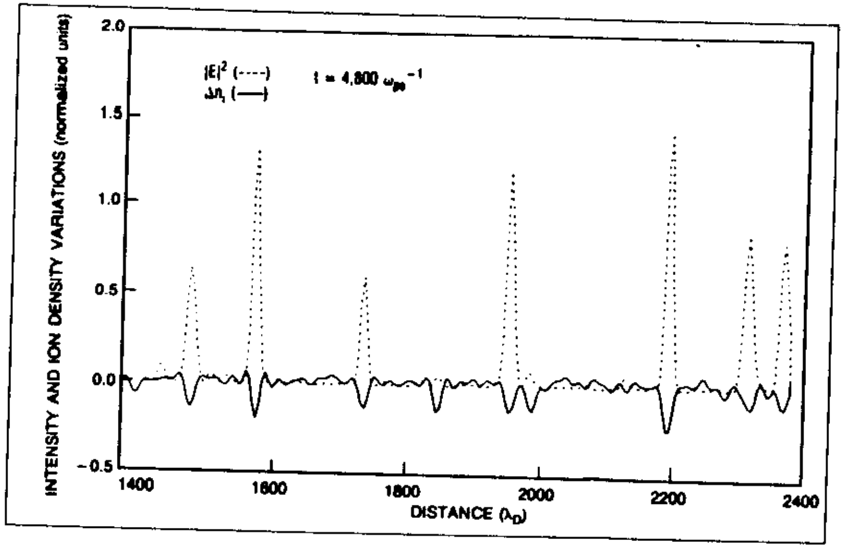

Fig. 9. Same as Fig. 7, for the range between 1400 and 2400 Debye lengths.

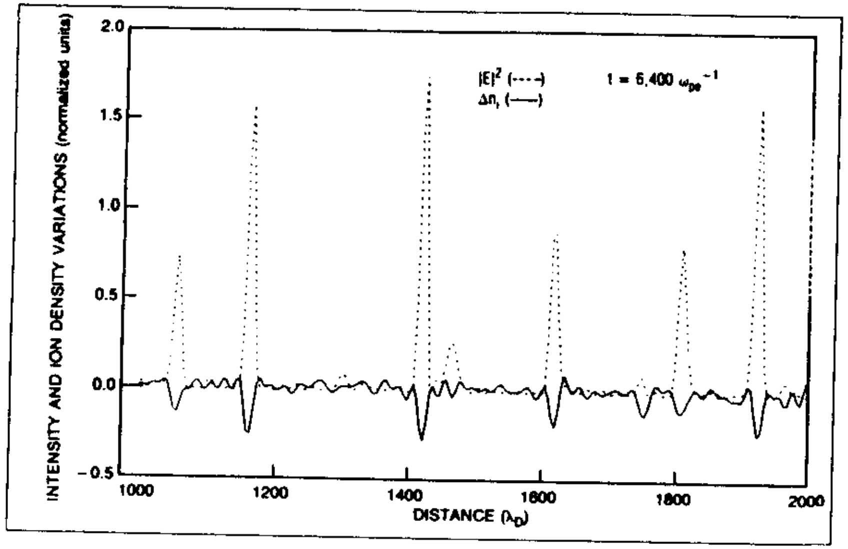

Fig. 10. Same as Fig. 8, for the range between 1000 and 2000 Debye lengths. Comparing the range between 1400 and 2000 λ_D, with the same range in the previous figure, one easily notes the burn-out and nucleation events occurring.

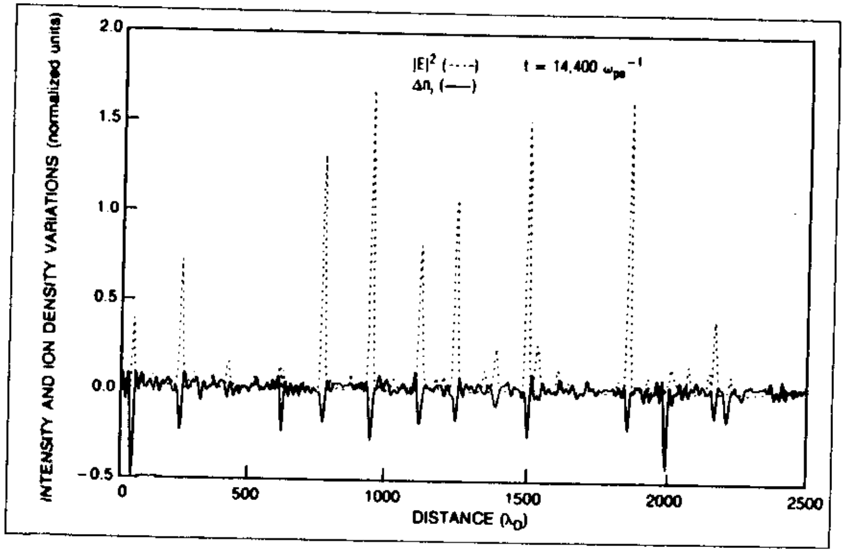

Fig. 11. Same as Fig. 2, for t=14,400 plasma periods. Note there are fewer solitons, the intensities have saturated, still, ion density depletions routinely reach over 50%! Several of the depletions appear burned-out.

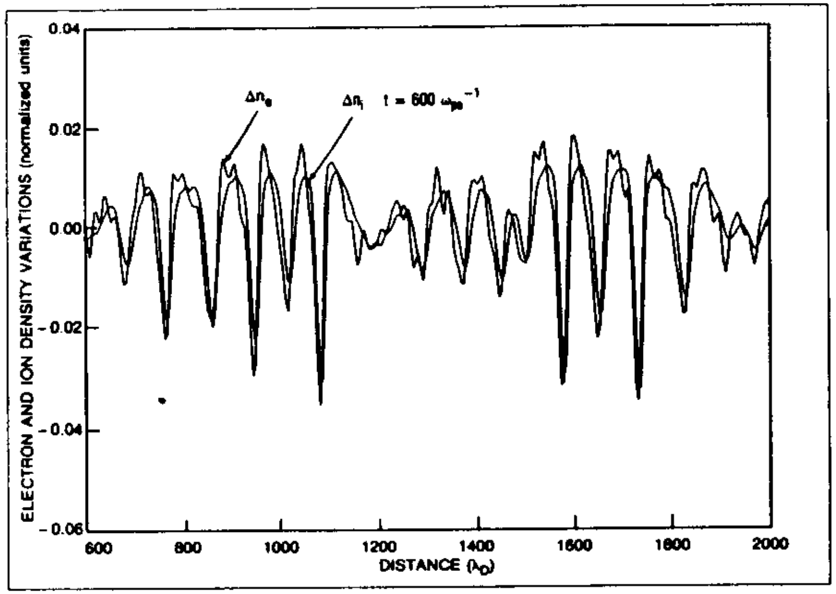

Fig. 12. Electron and ion densities normalized to the ambient density, as a function of position for t=600 plasma periods. Note charge separation effects are already clearly evident, the electron density trace having markedly more fluctuations in it.

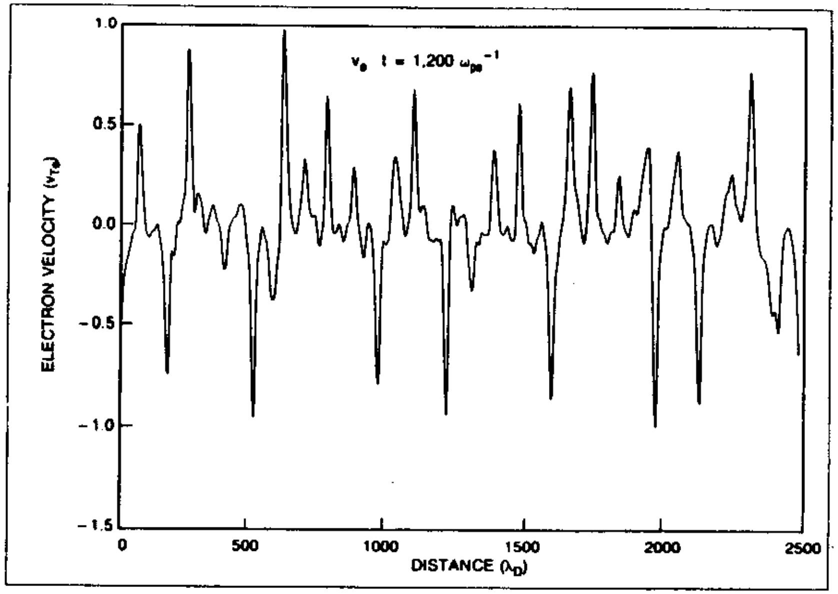

Fig. 13. Electron velocity (normalized to the thermal electron velocity, v_{Te}) as a function of position for t=1200 plasma periods. Note the magnitude of gradients. Gradients approaching infinity indicate the onset of wavebreaking.

damping and realistic driving terms to model actual experimental conditions, solutions in two dimensions, solutions in inhomogeneous plasmas, and the inclusion of electromagnetic terms. A new code which follows the evolution beyond the onset of wavebreaking is under construction. Successful implementation of these more general models will permit the exploration of the nonlinear evolution and saturation of SRS, SBS, and two-plasmon decay instabilities.

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