Analysis of the Inverted Double Layers Produced by Nonlinear Forces in a Laser-Produced Plasma

Heinrich Hora, Paraskevas Lalousis, and Shalom Eliezer[(a)]
Department of Theoretical Physics, University of New South Wales, Kensington-Sydney, Australia
(Received 21 February 1984)

By use of a hydrocode it is shown that the interaction of high-intensity light with an expanding plasma surface produces a positive plasma cloud followed by a negative plasma cloud. This result, which is opposite to that without the laser light, is the result of the nonlinear (ponderomotive) force.

PACS numbers: 52.35.Mw, 52.50.Jm

A well-known insufficiency of the earlier macroscopic two-fluid theory of plasmas[1] was the impossibility to reproduce directly Langmuir (electrostatic) waves and their coupling with electromagnetic waves because the theory needed the approximation of electric quasineutrality. Though phenomena of electric fields in plasmas were concluded in the surface of laser-produced plasmas,[2] or in cosmic plasmas,[3] the step towards a consequent macroscopic theory describing these phenomena was not possible before the approximation of quasineutrality could be overcome by a genuine two-fluid description with unrestricted electric fields.[4] The numerical models, however, needed time steps much shorter than the plasma oscillation period,[5] and finally resulted in detailed electric field mechanisms, such as plasma rotation in tokamaks, as a basic effect (and not as a higher order anomaly),[4] and in the first quantitative theory of the decrease of thermal conduction in pellet fusion.[6]

We report here on the evaluation of the theory to explain the observation of the measured double layers in laser-produced plasmas with an inversion of the polarity[7] for which we found a direct connection with the generation of cavitons due to nonlinear force action. Detailed experiments showed the surprising result that the first part of a laser-produced expanding plasma is positively charged followed by a negative plasma cloud within a temporal resolution of 1 nsec. This is an "inverted double layer" because any freely expanding plasma has first a negative and then a positive charge.[2,3] The experiment in Ref. 7 was calibrated *in situ* and therefore any regular double layer can precede the inverted double layer, only within a shorter time than the experimental resolution (1 nsec). The appearance of a strong inverted electric double layer in a laser-produced plasma can be analyzed from the following evaluation of a hydrodynamic computation of laser-plasma interaction where special attention has been given to the generation of electric fields and double layers in the interior of inhomogeneous plasma.

Macroscopic hydrodynamic computations could not cover these electrostatic mechanisms, as they were developed as one-fluid codes (WAZER, LASNEX, MEDUSA, etc.) and the two-fluid theory[1] was essentially based on electric quasineutrality of the plasma; the theory of the nonlinear forces in laser-produced plasmas required an extension to oscillating space charges and the addition of nonlinear terms.[8]

The fact that the nonlinear forces from the laser act on the plasma electrons and the ions follow electrostatically was the motivation for the development of a genuine two-fluid code for electrons and ions coupled by the Poisson equation. We derived from this code the generation, coupling, and collisional damping of electrostatic plasma oscillations by thermal (pressure) or electromagnetic (nonlinear force) driving of the plasma dynamics.[5] The generation of very high electric fields (more than 10^8 V/cm) for 10^{16}-W/cm^2 neodymium-glass laser irradiation was derived. Also without laser fields the electric fields were simply generated by gradients of the electron density and/or the temperature.

We use this code to study the sign of the space-charge densities for comparison with the measurement of the inverted double layers.[7] The code[5] uses one-dimensional hydrodynamics of the electrons and ion fluid with coupling by electric fields, viscosity, and thermalization according to the equipartition time. The laser fields are calculated from the Maxwellian equations with internal reflection using the spatial and time dependence of the optical constants including the nonlinear intensity dependence of the collision frequency. As the code was covering the electrostatic oscillations and had to follow time steps below a few femtoseconds, we could only follow the plasma dynamics to a few picoseconds where the inverted double layers appeared to be similar to the experiments in the nanosecond time scale.

The model uses a fully ionized hydrogen plasma of electron T_e and ion T_i temperatures of 1 keV, zero velocity v_e and v_i for electrons and ions, equal electron and ion densities $n_e = n_i$ with a parabolic distribution along the depth x for a layer of 25-μm thickness and a maximum near the cutoff density of 10^{21} cm^{-3}, all at time $t=0$ as initial conditions. For the first 0.5 psec, no laser is acting and the expansion of the plasma leads to fast oscillating fields and electron motion damped by collisions and results in electric fields and net velocity profiles similar to those described before.[5] At $t=0.5$ psec the laser of 1.06-μm wavelength is switched on with a constant intensity of 10^{16} W/cm^2 incident from the left-hand side (from $-x$). Figure 1 shows the ion-density profiles at the following times. At 0.6 psec, the profile became a little bit asymmetric compared with the fully symmetric parabolic profile up to 0.5 psec. The laser electric field E—calculated exactly with all internal reflection—produced a distribution of the energy density $E^2/8\pi$ as shown in Fig. 2. At 0.6 psec the nonlinear force $(\partial/\partial x)(E^2 + H^2)/8\pi$ with the laser magnetic field H including now its fully time-dependent interaction caused a faster motion of the ions to $-x$ near 5 μm than there was up to 0.5 psec ($|v_i| < 10^4$ cm/sec), Fig. 3. Due to the positive ion velocity for $x > 5$ μm, the ion density increases there, causing a higher dielectric swelling of $E^2/8\pi$ near 5 μm. The density develops then a minimum after 0.9 psec (caviton) which is strongest at 1.1 psec and is becoming weaker. The reason is that the caviton has built up a high ion (plasma) density near $x=0$ μm above cutoff through which nearly no light can penetrate (see the low field at 1.1 psec in Fig. 2) which is a self-quenching of the laser-plasma interaction.[6] The ions have reached velocities beyond 10^7 cm/sec near the caviton at this time. The strong negative gradient of the density at and around 1 μm when the caviton has been generated after 1 psec results in a pressure driving the ions toward $+x$ with a high positive velocity.

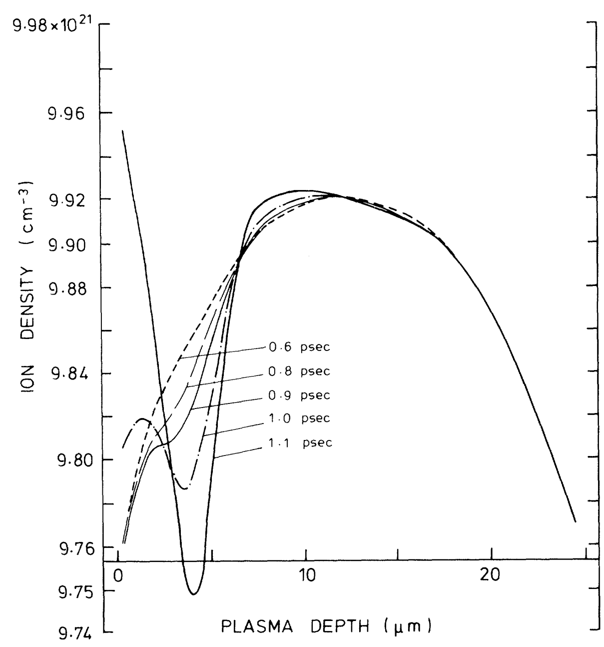

FIG. 1. Ion density n_i of the initially 25-μm-thick, initially symmetric, parabolic profile of an initially resting fully ionized hydrogen plasma of 1-keV initial temperatures, after a neodymium-glass laser intensity of 10^{16} W/cm^2 is incident from 0.5 psec from the left-hand side. The later-developed density minimum near a depth $x=7$ μm is the caviton.

This caviton generation is very similar to that known from single-fluid models.[8] We are able, however, to follow up the electrostatic fields and the resulting difference of the ion and electron densities which generate the space charges: Figure 4 shows these density differences $n_i - n_e$. At the right-hand end of the profile, near 25 μm, where no light is present, the plasma behaves normally. The more outside the plasma, the more it is negative according to the smeared Debye sheath due to the faster expanding electrons (where the complicated oscillations and damping process[4,5] had been shown before within the remaining faster net electron velocity and remaining electric field). At the other side of laser interaction, at x near 0 μm, the

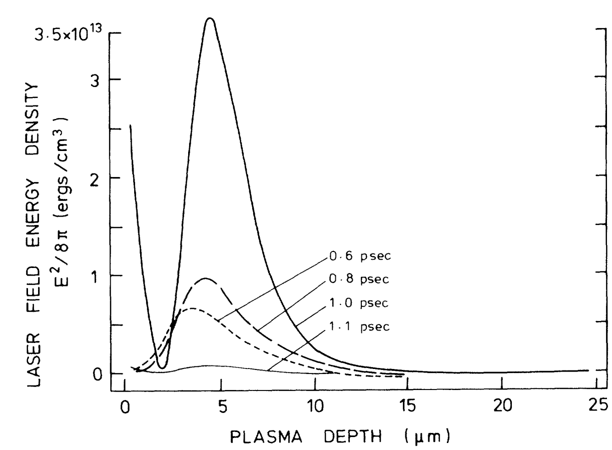

FIG. 2. Density of the electric field energy of the laser (without the electrostatic fields generated within the plasma) for the conditions as in Fig. 1.

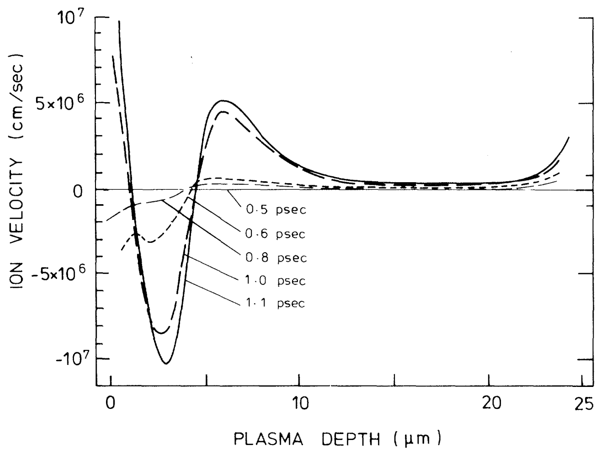

FIG. 3. Ion velocity profiles for the conditions of Figs. 1 and 2.

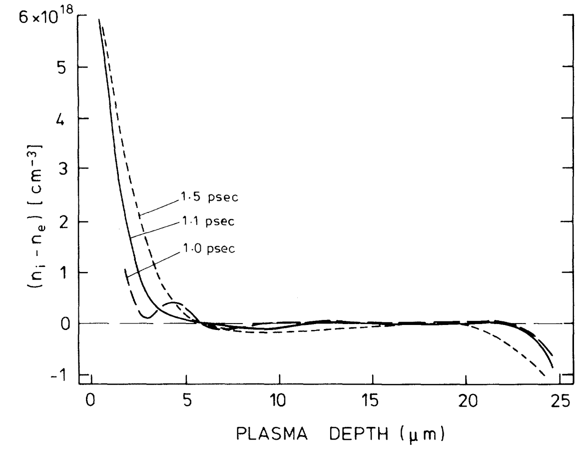

FIG. 4. The genuine Eulerian two-fluid code permits the evaluation of the unrestricted differences of the ion and electron densities $n_i - n_e$ for the cases of Figs. 1 to 3. At the left-hand laser-irradiated side appears the generation of high positive charge densities, followed on growing depth x by a negative charge density to zero difference. At the high-x end without laser light, the negative charge density of a freely expanding plasma surface appears.

complicated caviton process has produced a strong positively charged plasma cloud, sometimes even with oscillations, followed by a long negative plasma for $x > 6$ μm going to zero near 15 μm and from then on showing normal behavior as expected from a plasma without laser interaction.

As we had to use an Eulerian code in order to fix the spatial grid for the electric field calculation, we cannot follow up the processes for negative x (below the boundary conditions) with the given model. While it was necessary to use an Eulerian code, we had to overcome the then appearing problems of numerical diffusion from boundaries. Second-order extrapolation is applied at the boundaries. If extrapolation at the boundaries is performed only at the $N+\frac{1}{2}$ grid point in the auxiliary step and at the 1 grid point at the main step (as one is tempted to do at a first glance following the two-step Lax-Wendroff method), indeed a spurious wave is formed after a few time steps. This was overcome by numerically experimenting when computing the conservative variable at the $N+\frac{1}{2}$ and at the $\frac{1}{2}$ grid points[5] where results by Chu and Sereny and by Roache[9] were discussed.

Thus, we have shown hydrodynamically how the usual negative charge of a freely expanding plasma surface is generated while the laser interaction and caviton generation at high laser intensities with a predominance of the nonlinear forces produced first a positive plasma cloud followed by a negative plasma cloud in agreement with the measurements.[7]

This work was supported by the Australian Research Grant Scheme under Grant No. 81/15511 and by the Gordon and Mabel Godfrey Fund.

[(a)]On leave from Soreq Nuclear Research Centre, Yavne, Israel.

[1]A. Schlüter, Z. Naturforsch. **5A**, 72 (1950); L. Spitzer, Jr., *Physics of Fully Ionized Plasmas* (Wiley, New York, 1962).

[2]H. Hora, *Laser Plasmas and Nuclear Energy* (Plenum, New York, 1975).

[3]H. Alfven, *Cosmic Plasmas* (Reidel, Dordrecht, 1981); *Second International Symposium on Double Layers,* edited by R. Schrittwieser (Institute of Theoretical Physics, Innsbruck, Austria, 1984).

[4]H. Hora, P. Lalousis, and D. A. Jones, Phys. Lett. **99A**, 89 (1983).

[5]P. Lalousis and H. Hora, Laser Part. Beams **1**, 238 (1983); *Computational Techniques and Applications: CTAC-83,* edited by J. Noye and C. Fletcher (Elsevier, North Holland, 1984), p. 699; P. Lalousis, Ph.D. thesis, University of New South Wales, 1983 (unpublished).

[6]H. Hora and G. H. Miley, Laser Focus **20**, 57 (1984).

[7]S. Eliezer and A. Ludminsky, Laser Part. Beams **1**, 251 (1983).

[8]H. Hora, Phys. Fluids **12**, 182 (1969), and **17**, 939 (1974), and *Physics of Laser Driven Plasmas* (Wiley, New York, 1981).

[9]C. K. Chu and A. Sereny, J. Comput. Phys. **15**, 476 (1974); P. J. Roache, *Computational Fluid Dynamics* (Hermosa, Albuquerque, 1972).