Laser and Particle Beams (1995), *vol.* 13, *no.* 3, *pp.* 441–447
Printed in the United States of America

How double layers accelerate charged particles

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(Received 1 October 1993; revised 21 October 1994; accepted 11 November 1994)

After the theory of dynamic double layers in laser-produced plasmas arrived at several significant results in agreement with measurement, including particle acceleration, a clarification was given to the paper by Bryant *et al.* (1992) negating such acceleration. The discrepancy seems to be in the definition of static double layers in contradiction with dynamic double layers that are created in laser-induced plasma. We present here new results on the acceleration of electrons in a laser-irradiated plasma by double layer mechanisms. A simple analytical example is given.

1. Introduction

In a recent paper it was stated that "double layers are not particle accelerators" (Bryant *et al.* 1992). This seems to be a criticism of charged particle acceleration by double layers in space, as was calculated, for example, in Knorr and Goerz (1974), Goerz (1979), Alfven (1981, 1988), Falthammer *et al.* (1987), and Peratt (1988). We claim that "stationary" double layers do not accelerate charged particles as stated in (Bryant *et al.* 1992) while "nonstationary" double layers can accelerate as seems to be the case in Knorr and Goerz (1974), Goerz (1979), Alfven (1981, 1988), Falthammer *et al.* (1987), and Peratt (1988). In this paper, we demonstrate that a laser-produced double layer (Eliezer & Hora 1989) can accelerate electrons.

Stationary double layers are those between a wall and a stationary plasma or between two or three plasmas of different temperature and/or density in the formation by duo or triple plasma devices (Hershkovitz 1985). Since the electric field is static as a result of the stationary conditions, any closed integral in the plasma, including the double layer, satisfies the condition $\oint E \cdot ds = 0$, and therefore no acceleration is possible in agreement with Bryant *et al.* (1992).

The appearance of double layers in laser produced plasmas (Eliezer & Hora 1989; Hora 1991) was related to the question of the generation of anomalously energetic ions and the action of the nonlinear force. Linlor (1963) had observed keV ions at laser irradiation with powers above (the threshold of about) 1 MW contrary to the few eV (thermal) ions below 1 MW power. The nonlinear (ponderomotive) force acceleration mechanism was introduced (Hora 1969, 1991) in order to reproduce the measured (nonthermal) energetic ions; this requires the involvement of the ponderomotive self-focusing (Hora 1991) with the thresholds of about MW power. Moreover, the double layer acceleration in the plasma surface was well measured later (Wagli & Donalson 1976), as proved by the identification of one group of keV ions which were independent of the optical polarization.

 0263-0346/95 $11.00 + .10

Apart from this very first involvement of the electric double layer in laser-produced plasmas, another impact came from the following basic question about the nonlinear force (Hora 1991). The force density (Hora 1969) was indeed the result of the space neutral theory of Schluter, which explained that the whole plasma as a block was moved by the gradients of the electromagnetic laser field. Another model arriving at the same nonlinear forces was possible from a single electron description. The inhomogeneous laser field caused a quiver drift of the electron arriving at the same acceleration as known from the nonlinear force (Hora 1991). The inertia was not given by the electrons, but by the ions. This was the motivation to ask the question, in what way are high electric fields being built up when the laser takes the whole electron cloud for acceleration and the ions have to follow by field attachment. These electric fields could not be expected for Schluter's model because these internal electric fields were intentionally neglected.

The way out was to develop a genuine two-fluid model (Lalousis & Hora 1983; Aydin & Hora 1992) for the fully ionized plasma consisting of the electron fluid and the ion fluid between which a coupling by electric fields is present. In one spatial dimension, this is expressed by Poisson's equation, and in three dimensions, one has to add the whole Maxwellian equations resulting in the rather complex megagauss spontaneous magnetic fields as observed in laser-produced plasmas (Stamper 1991). This could be seen from an extensive numerical evaluation (Lalousis & Hora 1983; Aydin & Hora 1992) of the motion of the coupled two fluids, for example, of a deuterium plasma in one spatial dimension for electron densities around 10^{21} cm^{-3} (corresponding to the critical cut-off density of neodymium glass laser irradiation). The numerical difficulty consists in the fact that the temporal steps have to be 0.1 fsec in order to be about 10 steps per fastest plasma oscillation, while the integration of the whole dynamic system has to arrive at least to several psec for the experimental comparison. These numerical difficulties were solved in Lalousis and Hora (1983) and Aydin and Hora (1992).

This hydrodynamic model, however, had the disadvantage that at each time step, the equilibration of the energy distribution of the electrons and ions had to arrive at Maxwellian distributions in order to follow the hydrodynamics with temperatures T of the ions (index i) and electrons (index e). For the one-dimensional problems, one then had the seven quantities for electrons and ions, the two temperatures T_i and T_e, the two densities n_i and n_e, the two velocities v_i and v_e, and the x-component of the electric field E, all depending on x and t. This had to be solved for special initial and boundary values from the following seven differential equations: two of continuity, two of motion, two of energy conservation, and the Poisson equation. Realistic plasmas with collisions, viscosity, and the equipartition time for temperature exchange between the two fluids were included. The transversal laser field (perpendicular to x) was appearing only in the nonlinear force terms, with the squares of the electric and magnetic laser fields E_L and H_L as contributions to the equation of motion of the electrons and further, as a heat source of collisional absorption in the electron equation of energy conservation. In order to calculate the laser field from the boundary conditions of some temporal incident laser intensity, the Maxwellian equations had to be solved for the complete inhomogeneous and dynamically developing plasma at each time step, with the boundary condition of evanescent waves only in the superdense plasma.

This real-time realistic plasma then revealed plasma properties never before calculated. First, without any laser, one could see how a plasma expands into vacuum. The longitudinal electric field E between the electrons and ions was evaluated for the following initial conditions: a deuterium plasma of 1 keV electron and ion temperature with zero velocity, and a density ramp (for electrons and ions the same at the beginning) growing linearly from 5×10^{18} cm^{-3} at $x = 0$ to twice this value at $x = 10$ μm. The field is then zero at $t = 0$ for growing time (given in periods of the smallest plasma frequency); one sees a very hefty oscillation of the E-field. This corresponds to the fact that the electrons, with their small mass, leave the ramp very quickly by thermal hydrodynamic motion until they are stopped and returned by the E-field. They do not return to the initial position since the ions are also moving hydrodynamically due to their temperature and the pressure gradient; no change in the sign of the electric field occurs. The oscillation is then damped and after 40 periods (by collisions), a nearly stationary field profile has been reached. The derived electric fields of MV/cm are expected since there is a temperature of keV and a plasma decay of 10^{-3} cm.

By irradiating a plasma profile with a highly bent parabolic initial density profile of 25 wave length thickness with neodymium glass laser radiation of 10^{17} W/cm^2 intensity, the full dynamics of laser-produced plasmas appears. One notes the generation of the density minimum (caviton) and the speeding up of the plasma to velocities of a few 10^8 cm/sec against the laser light (Hora 1991) within 1 or 2 psec interaction in agreement with measurements and rough hydrodynamic estimation from the magnitude of the very high driving nonlinear force. What can be seen on top is the longitudinal electric field between the electron and ion fluid with a complicated large amplitude (10^9 V/cm) oscillation and with the recognition of Pseudo-Langmiur waves (Eliezer & Hora 1989). Due to the caviton, an inverted double layer appears (Hora *et al.* 1989) in agreement with measurements (Eliezer & Ludmirsky 1983).

It is evident that the longitudinal electric field is no longer a conservative electrostatic field, that is, $\oint E \cdot ds \neq 0$. Any closed-loop path integration of this strongly time dependent $E(x,t)$ is then different from zero. One example of this type of energy gain and automatic acceleration of electrons within such a dynamically developing inhomogeneous plasma is shown in figure 1 of Hora *et al.* (1989) for an initial parabolic density profile as described before (Szichman 1988). For such a complicated time dependence of the internal electric field in a laser-produced plasma, we have evaluated the motion of electrons. An electron is assumed to start to move from $x = 7$ micrometer (figure 1) against the laser light (coming from $x = 0$) where the initial energies of the electrons are for the following three cases: 1, 5, or 30 keV. The energy plotted in figure 1 is that which the electron is gaining during this motion. We see that the electrons can be speeded up to 140 keV energy when leaving the plasma at the side of the laser irradiation. However, a slowing down could well occur in the reverse direction and the 5 keV electron, for example, is then stopped at about 1.2 micrometers at the time when the other electrons are leaving the plasma.

2. Discussion

We would like to refer to some confusion related to the subject of double layers (DL).

2.1. *Definition*

Double layers are regions of non-neutral plasma. DL consist of two adjacent non-neutral plasmas of opposite charge. DL is a special case of a more general phenomena which consists of multiple DL (Hershkovitz 1985) (triple layers, etc.). The DL can be *stable* or *transient*. There are steady-state or *electrostatic DL* and there are dynamic or *time dependent* (Hershkovitz 1985) *DL*. The steady-state DL can be BGK solutions (Bernstein *et al.* 1957). One possible form of dynamic DL is referred to in the literature (DeGroot *et al.* 1977; Bharuthram & Shukla 1986) as ion acoustic double layers. Another possible form of dynamic DL is associated with collisionless shocks (Lembege & Dawson 1989). It is interesting to quote from the abstract of Lembege and Dawson (1989): "... a double layer forms at the shock front ... *Electrons are strongly accelerated through the double layers. ...*" The dynamic DL are time-dependent or transient phenomena and they are defined in the vast literature of DL. These DL are associated with the presence of turbulence (DeGroot *et al.*

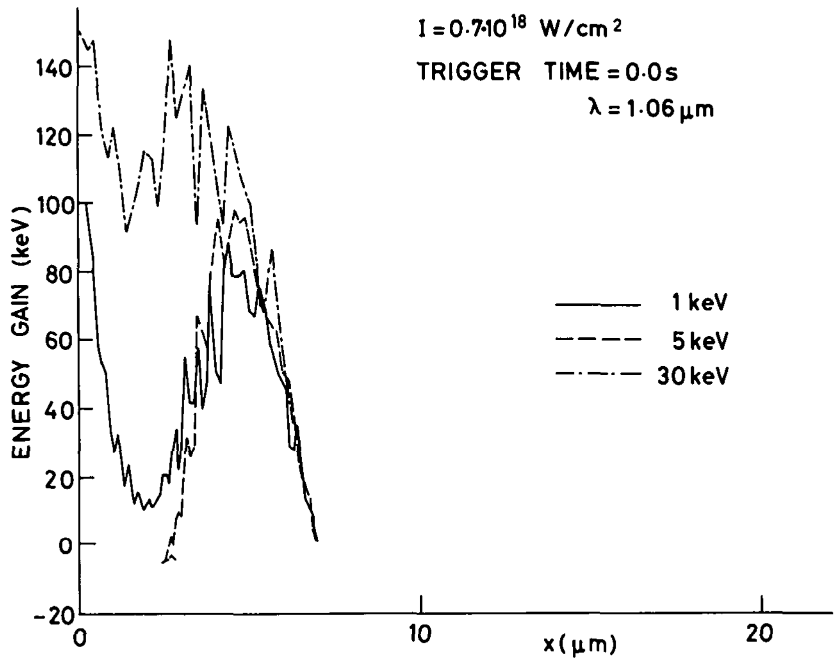

FIGURE 1. Computation of the energy gained by electrons starting with initial energies of 1, 5, or 30 keV at times zero from $x = 7$ μm towards negative x in a 20 wavelength thick plasma slab of initially parabolic density profile (Hora *et al.* 1984, 1989) at irradiation (from the left-hand side) by a neodymium glass laser of $7 \cdot 10^{17}$ W/cm^2 intensity.

1977; Chan & Hershkovitz 1982), phase space vortices near the DL, plasma ionization, ion acoustic fluctuations, shock waves, etc. In high irradiance laser-plasma interaction, the DL are time dependent, that is, the associated charges and electric field are changing on a time scale smaller than the time of flight of a particle through the DL.

2.2. *DL-particle interaction*

In order to clarify this point, an analytical model is considered in one dimension (1D). A charge density $\rho(x,t)$ is given in equation (1):

$$\frac{1}{4\pi}\frac{d}{dx}E(x,t) = \rho(x,t) = \frac{m}{2\pi e}[u_1 - u_0]\delta(t)\cdot\exp\left[\frac{-x^2}{\sigma^2}\right]\frac{[-3\sigma^2 + 2x^2]}{\sigma^4}, \qquad (1)$$

where E is the electric field, m and e are the mass and charge of the particle (e.g., electron), $(u_1 - u_0)$ is at this stage a parameter with a dimension of velocity, and σ is the space scale length, usually of the order of Debye length. In this example, the main assumption is the instantaneous "action" or existence of the charge distribution described by the Dirac delta function $\delta(t)$. One can consider this type of DL as a "fluctuation" or as a short phenomenon on a time scale of the time of flight of a particle through the DL. The solution of equation (1) is given by

$$E(x,t) = \frac{m}{e}[u_1 - u_0]\delta(t)\exp\left[\frac{-x^2}{\sigma^2}\right]\frac{[\sigma^2 - 2x^2]}{\sigma^2}. \qquad (2)$$

The equation of motion of the particle in the field of the DL is given by

$$m\frac{d}{dt}\left[\frac{d}{dt}x(t)\right] = eE(x(t),t). \tag{3}$$

The solution of the equations of motion for the trajectory $x(t)$, the particle velocity $v(t)$, and its acceleration $a(t)$ are

$$x(t) = u_0 t + [u_1 - u_0]\theta(t)t, \tag{4}$$

$$\frac{d}{dt}x(t) = v(t) = [u_1 - u_0]\theta(t) + u_0, \tag{5}$$

$$\frac{d}{dt}v(t) = a(t) = [u_1 - u_0]\delta(t). \tag{6}$$

At this point, it is worth mentioning that solutions (4), (5), and (6) are correct for any electric field of the type $c\cdot f(x)\delta(t)$ with $f(x=0)=1$ and $c = m(u_1 - u_0)/e$. The acceleration of a charged particle crossing the DL (from $-\infty$ to $+\infty$) is given by

$$e\int_{-\infty}^{\infty} E(x(t),t)dx = e\int_{-\infty}^{\infty} E(x(t),t)\cdot\frac{d}{dt}x(t)dt = \frac{1}{2}m[u_1^2 - u_0^2]. \tag{7}$$

It is clear at this stage that the particle was accelerated from speed u_0 to u_1 and gained a kinetic energy as given by equation (7).

2.3. *The integral* $\oint\vec{E}\cdot d\vec{s}$

From Maxwell equations, it is clear that for $\vec{\nabla}\times\vec{E}\neq 0$, one has trajectories that satisfy $\oint\vec{E}\cdot d\vec{s}\neq 0$ and in this case, acceleration of particles (crossing a DL) is possible. However, for electrostatic fields, one has

$$\oint\vec{E}\cdot d\vec{s} = \int_{-\infty}^{\infty} E(x(t))dx = 0, \tag{8}$$

Since the line integral along an infinite semicircle vanishes because for $r\rightarrow\infty : E\sim r^{-n}$, $n\geq 1+\epsilon$, $\epsilon > 0$. However, for dynamic fields, one has

$$\int_{-\infty}^{\infty} E(x(t),t)dx \neq 0, \tag{9}$$

and acceleration is possible as shown explicitly in equation (7). This example may clarify the connection between closed integrals and their relevance to situations where particles do not follow closed trajectories.

2.4. *The 1D problem*

One-dimensional DL is usually described by non-neutral plasmas with an infinite lateral extent. In this case, one has a zero electric field on each side of the DL and the Poisson equation is not satisfied. Note also that for 1D, two point charges (+ and −) are equivalent to a capacitor with infinite lateral extent. For practical problems, one needs a finite lateral extent which in 1D is equivalent to introducing multiple DL (more than two). This fact is necessary in order to satisfy the Maxwell equations. The 1D example given analytically above (equation (2)) is described in figure 2. As one can see, the electric field changes signs outside the "main" DL (in order to satisfy $\oint\vec{E}\cdot d\vec{s} = 0$ for the electrostatic case).

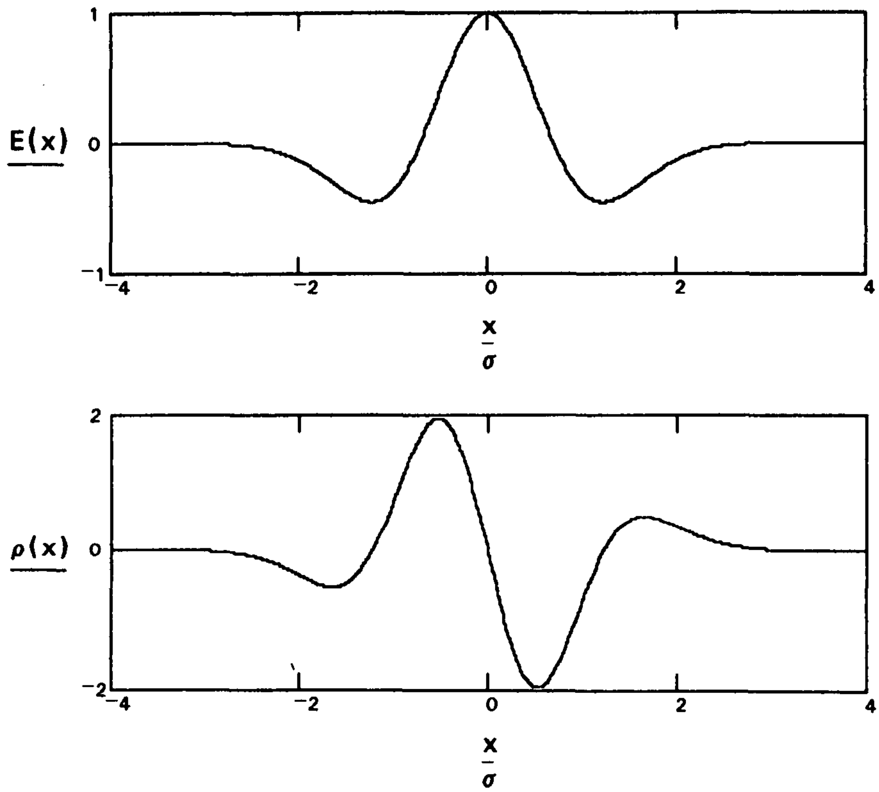

FIGURE 2. The charge distribution ρ and the electric field E of a one-dimensional DL.

This implies a charge distribution with more than two non-neutral plasma layers (four in our example).

2.5. *The laser-plasma DL accelerator*

In laser–plasma interaction, "fast electrons" were detected. One interpretation of this phenomenon was associated with dynamic DL. In particular, the results of a simulation are given in figure 1. However, in those cases, the acceleration is for a particle "created" within the DL. In this case, the integral (7) is taken between a point inside the DL and infinity. Such acceleration or deceleration is shown in figure 1.

3. Conclusion

In summary, in this paper it is demonstrated that a dynamic (i.e., time dependent) DL can accelerate charged particles (Raadu 1989). An analytic calculation (equation (7)) as well as a laser plasma simulation (figure 1) show the acceleration effect of a DL. The existence of DL in laser-produced plasma in the outer corona was detected directly by the deflection of a probing beam (Mendel & Olsen 1975; Ehler 1975) and by Rogowski coils (Eliezer & Ludmirsky 1983; Ludmirsky *et al.* 1985). Therefore, similar to DL in astrophysics (Raadu 1989), the DL might play an important role in laser–plasma interaction.

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