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Acceleration of electrons by a laser pulse in a tube

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In this paper we consider a scheme for laser driven electron acceleration in which a short intense laser pulse travels along a hollow tube, ionizing and heating the walls as it goes. Hot electrons expanding off the walls produce a large negative potential behind the pulse and the resulting potential gradient along the tube can be used to accelerate electrons. Computer simulations of this process suggest that accelerating fields in excess of 10 GeV/m can be reached with currently available technology and that accelerated electron bunches are well-focused on the axis of the tube. It is suggested that this scheme may have advantages over beat wave and wake field schemes, in terms of the controllability of the speed and phasing of the accelerating potential. © *2000 American Institute of Physics.* [S1070-664X(00)05107-7]

I. INTRODUCTION

Particle acceleration using lasers has been investigated extensively ever since the original suggestion of Tajima and Dawson.[1] An overview of the development of the subject up to 1996 can be found in a review article by Esarey *et al.*[2] Most of the work in this area has focused on beat wave and wakefield schemes, both proposed in the original paper,[1] in which the acceleration is produced by plasma waves with phase velocities just below the velocity of light excited in a uniform plasma. Particles whose speed matches the phase velocity are accelerated in the longitudinal field of the wave. Some recent experiments showing effective electron acceleration rely on self modulation, a process similar in principle to the beat wave, but with a frequency shifted wave being generated spontaneously from a single frequency pulse via forward Raman scattering, rather than the pulse containing waves of two frequencies.[3]

In this paper we discuss an alternative scheme of particle acceleration in which a very short, intense laser pulse is directed down a hollow cylindrical tube. Simulations[4] and experiments[5] have shown that when an intense laser pulse is incident on a solid target there is rapid ionization followed by heating of the plasma to very high temperatures, of the order of hundreds of keV. On a time scale on which electrons can move but ions do not have time to respond there is a large negative potential in the electron cloud expanding from the surface. If the pulse is traveling along a tube and electrons expand into it, then a simple calculation, which we give below, indicates that when thermal equilibrium is reached the negative potential in the center of the tube, in volts, may be several times the electron temperature, in eV. Ahead of the pulse, the potential must, of course, be zero, so the result is a longitudinal potential ramp, moving with the pulse and capable of accelerating electrons. Essentially the same idea was given by Bulanov *et al.*[6] some years ago but, as far as we are aware, has not been pursued in any detail since. Other work on the use of capillaries with which we are familiar, for example that of Dorchies *et al.*,[7] discusses their use to create long uniform plasmas for conventional beat wave or wakefield experiments. In this paper we present some simple analytic estimates and computer simulations which indicate that the use of a short pulse to create an ionization and heating front moving down a tube may be capable of generating longitudinal accelerating fields of the order of 10^{10} V/m. Initial results indicate that test particles accelerated by this field remain quite well focused in the center of the tube. We suggest that a scheme of this sort may offer some advantages over schemes based on using pre-formed plasmas, since the velocity of the pulse is that of propagation in a waveguide and is perhaps more easily controllable than the group velocity in a plasma.

II. SOME ANALYTIC ESTIMATES

Before describing the results of computer simulations we present a few simple order of magnitude estimates which show the basis of the method. Suppose that a short pulse propagates down a narrow tube, ionizing and heating the walls, so that the electron temperature is T_e. If, behind the pulse, there is a region where the electrons have reached thermal equilibrium, while the ions have not had time to move any significant distance then, if the longitudinal potential variation can be neglected, the potential ϕ is given by Poisson's equation,

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\phi}{dr}\right)=-\frac{e}{\epsilon_0}\left(N(r)-N_0\exp\left(\frac{e\phi}{T_e}\right)\right), \tag{1}$$

where $N(r)$, the ion density in the solid, is taken to be zero for $r<R$, with R the radius of the tube, and N_0 for $r>R$. It is convenient to take ϕ in units of T_e/e and length in units of

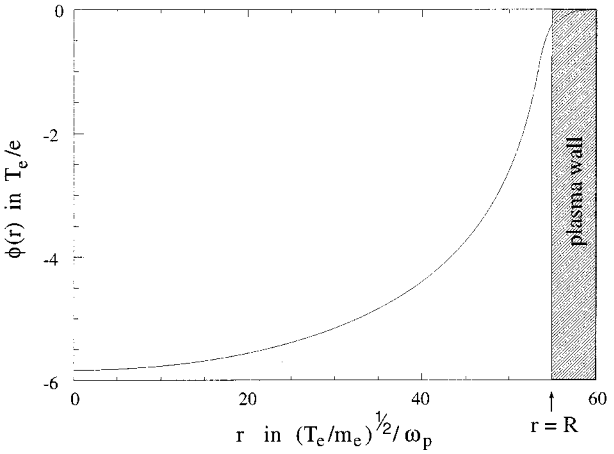

FIG. 1. The electrostatic potential ϕ in T_e/e for a cylindrical tube as a function of the tube radius r (in $\sqrt{T_e/m_e}/\omega_p$). The ion density is zero inside the hollow tube ($0<r<50$) and N_0 in the plasma wall ($r>50$). The potential at the center of the tube (in eV) is about six times larger than the plasma electron temperature T_e (in eV).

$(1/\omega_p)\sqrt{T_e/m_e}$ where ω_p is the plasma frequency corresponding to the solid density. In these units Eq. (1) becomes

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\phi}{dr}\right)=-(\tilde{N}(r)-\exp(\phi)), \tag{2}$$

where $\tilde{N}$ is 0 for $r<R$ (in dimensionless units) and 1 otherwise. This equation has to be solved with $\phi'=0$ at $r=0$ and $\phi\rightarrow 0$ for large r. Figure 1 shows a typical solution with a dimensionless radius of 50. This substantiates our claim that the potential (in V) at the center may be several times the electron temperature (in eV). While we have used a simple Boltzmann distribution for the hot electron energy, this is not an essential feature and qualitatively similar behavior would obviously be obtained from any distribution with a population of hot electrons.

For acceleration along the tube what interests us is of course the longitudinal potential gradient, not the radial variation. However, what the above calculation shows is that we may expect a potential jump from 0 in front of the pulse to a large negative value behind the pulse in the region where hot electrons have been blown off the wall. The precise details of the potential variation in the neighborhood of the pulse cannot be obtained analytically, but as a simple estimate let us suppose that the jump occurs over a length of the order of the tube radius. If we assume an electron temperature of a few hundred keV then we may have a total potential jump of the order of 1 MeV and if the tube radius is a few microns then the longitudinal field can be estimated to be of the order of 10^{11} V/m. Our computer simulations show that this is perhaps a somewhat over-optimistic result, but even accelerating fields an order of magnitude less than this would be very useful for electron acceleration. Another important question is whether the potential structure behind the pulse produces any strong defocusing of an electron bunch. This, again, is a difficult question to answer analytically. However, our computer simulations of bunches of test particles being accelerated in the tube do not seem to show any catastrophic defocusing effect. On the contrary there seems to be a focusing effect, probably because the front of the electron cloud has a cone shape so that electrostatic repulsion from the leading edge of the cloud will push the test particles towards the axis. On the other hand it has to be borne in mind that we have only been able to follow the particles for a rather short distance. Before turning to the simulation results let us make one or two more general comments on the laser pulse requirements. The pulse needs to be just long enough to heat the electrons on the surface of the solid and create the potential jump. If it lasts too long it will heat further cold electrons drawn in as the hot electrons drive a heat front into the solid. Another way of looking at things is to see that the transfer of energy to the accelerated electron bunch comes about because of the electrostatic repulsion between the negative charge on the bunch and the electrons being blown off the wall by the laser. There is no point in heating electrons long after the accelerated bunch has passed. Also with a very short pulse, the accelerated bunch can lie behind the pulse and not be disrupted by its field. Having made these estimates and general comments, we now turn to the simulation results.

III. SIMULATION RESULTS

For our numerical investigation, we developed a two-dimensional, particle-in-cell (2-D3V-PIC) code[8] capable of simulating the propagation of laser light along a slot rather than a tube. This reduces the amount of time and memory required for the computations while reproducing the essential features of the effects we are looking at. While the particle momenta, the electric currents as well as the electromagnetic fields are resolved in all three dimensions, the plasma electron positions are updated in two spatial dimensions only. The plasma ions, on the other hand, are simulated by a uniform background charge inside the channel walls, approximating the effect of heavy (and thus comparatively slow moving) ions. A typical setup is shown in Fig. 2. The simulation runs on a grid with up to 4000 × 800 grid points and about 25 macroelectrons per cell along the channel walls and covers an area of about $1000\times 200(c/\omega_p)^2$. In these simulations, we initialize an intense, short laser pulse in vacuum and let it propagate toward a channel with walls of preionized, overdense, cold plasma. The plasma electrons are allowed to move along the direction of laser pulse propagation as well as in one perpendicular direction. The polarization of the pulse can be chosen parallel or perpendicular to the channel walls, however, in this article we present the results from a perpendicular polarization (TM wave) only since such waves heat the plasma more efficiently via Brunel heating.[9] Since ionization will take place at the leading edge of the laser pulse, it is not expected to change the characteristics of the acceleration mechanism for high-intensity pulses and is therefore left out.

In our simulations, we usually chose a system with the following parameters (the values in parentheses correspond to a laser wavelength of 800 nm): The initially cold plasma was 5.25 times overdense (1.7×10^{21} cm^{-3}), the channel width about 9.6λ (7.6 μm), the full length of the laser pulse

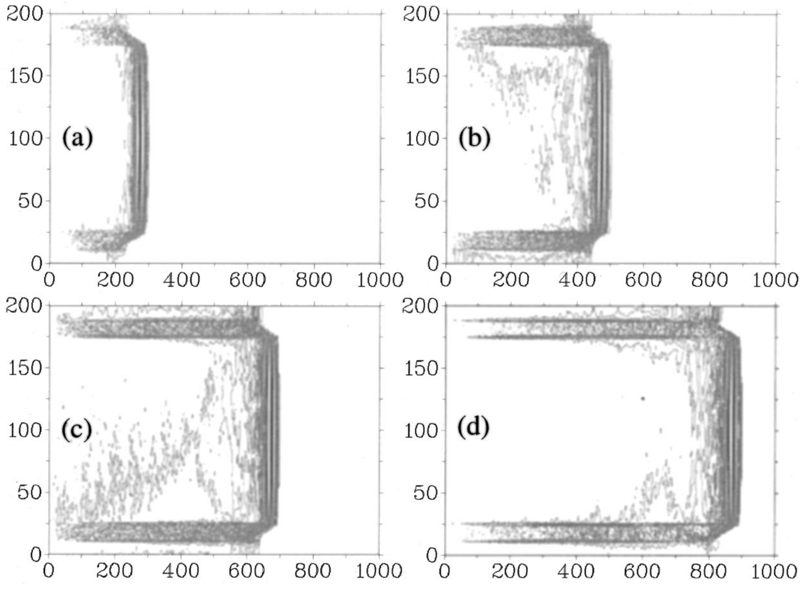

FIG. 2. The transverse electric field at $300/\omega_p$ (a), $500/\omega_p$ (b), $700/\omega_p$ (c), and $900/\omega_p$ (d) after the laser pulse launch from the left boundary of the simulation box. x and y positions are in c/ω_p, the laser pulse has a total length of about 3λ and the plasma density of the channel walls was 5.25 times overcritical ($\omega_p/\omega = 2.5$).

($\cos^2$ envelope) about 3.2λ (8.5 fs), and the peak field strength $a_0 = eE_{\max}/(m_e\omega c) = 3$ ($I_{\max} = 2\times 10^{19}$ W/cm^2). The pulse was initialized in vacuum and had a super-Gaussian transverse profile slightly larger than the separation of the channel walls. As it hits the channel entrance, part of the pulse is scattered and/or reflected such that only a fraction (about 70%) of the electromagnetic energy enters the structure. Once the pulse has entered the plasma channel, it propagates stably at a constant speed close to the speed of light and loses energy to the heating of the plasma walls only.

As the laser pulse is propagating along the channel, hot electrons leave the channel walls and form a cone-shaped electron cloud behind the pulse (Fig. 3). Negatively charged particles ahead of the electron cloud experience an accelerating force along the direction of laser pulse propagation. For a more quantitative statement, we allowed test particles to move along the channel. These test particles did not contribute to the charge density or the electric currents but fully responded to the fields present. They can thus be thought of as a rather low-density beam of electrons. This cold beam was injected right behind the laser pulse (to avoid transverse acceleration by the transverse electric field of the pulse) at a speed of $0.9c$ (661 keV). Figure 4 shows the evolution of this electron beam as it propagates along the channel. As the electron cloud builds up slowly, the accelerating fields become strong only at the end of our simulation. In fact, due to scattered light, some of the test electrons undergo some deceleration and spatial defocusing at the channel entrance [Figs. 4(a) and 5]. Once the cone-shaped electron cloud has formed, test particles ahead of this acceleration structure even experience some spatial focusing as well as strong acceleration. However, spatial focusing is accompanied by a spread in the energy distribution (Fig. 4) such that the beam emittance seems to be more or less conserved in the acceleration region.

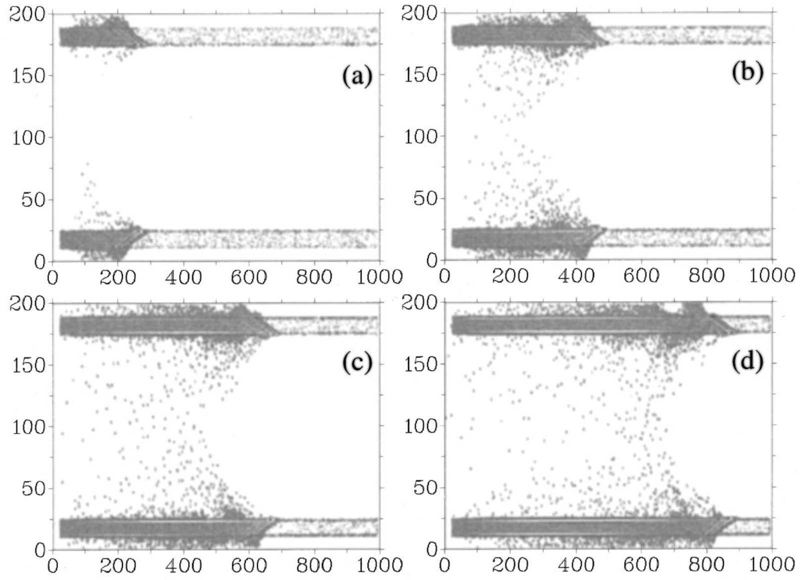

FIG. 3. The electron densities at $300/\omega_p$ (a), $500/\omega_p$ (b), $700/\omega_p$ (c), and $900/\omega_p$ (d) after the launch of the laser pulse. The electrons are streaming into the channel, forming a cone-shaped electron cloud behind the laser pulse's position.

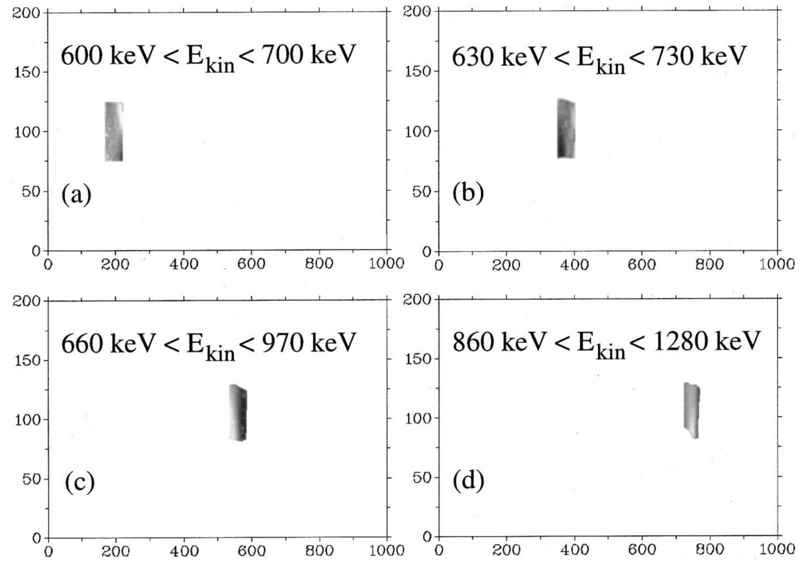

FIG. 4. Contour plots of the test particles at $300/\omega_p$ (a), $500/\omega_p$ (b), $700/\omega_p$ (c), and $900/\omega_p$ (d) after the launch of the laser pulse. While the spread in energy increases, the beam undergoes spatial focusing. The peak accelerating field can be estimated to exceed 20 GeV/m for a laser wavelength of 800 nm.

Finally, as the pulse loses its electromagnetic energy due to the heating of the plasma electrons along the walls, the formation of the accelerating structure becomes less efficient and the accelerating gradient less steep. In our numerical simulation, this effect becomes visible at the end of the run ($900/\omega_p$ to $1000/\omega_p$ in Fig. 5). While the acceleration of electrons is ultimately limited by this depletion length, the energy loss rate for a real laser pulse is expected to be much lower as the real pulse is likely to have a larger channel radius to laser wavelength ratio than the one in our simulations: As the pulse energy (at the same laser intensity) will increase with the square of the channel radius, the area to be heated increases only directly proportional to the radius.

IV. DISCUSSION

The simulation results show that for fields strengths in the pulse corresponding to an energy flux of the order of 10^{18}–10^{19} W/cm^2 there is indeed strong heating of the electrons at the surface of the wall and the development of a longitudinal field component. For the short pulses we use, this accelerating field is strongest behind the pulse, so that electrons can be accelerated in a region where they are not affected by the field of the pulse. When a bunch of test electrons is injected into the system we see acceleration corresponding to longitudinal fields of more that 10^{10} V/m. Also, although the shape of a bunch is distorted slightly as it travels, there is no sign of any tendency for the bunch to break up or for electrons to be deflected onto the walls. In fact it appears that there is a tendency for the beam to be focused onto the axis of the tube.

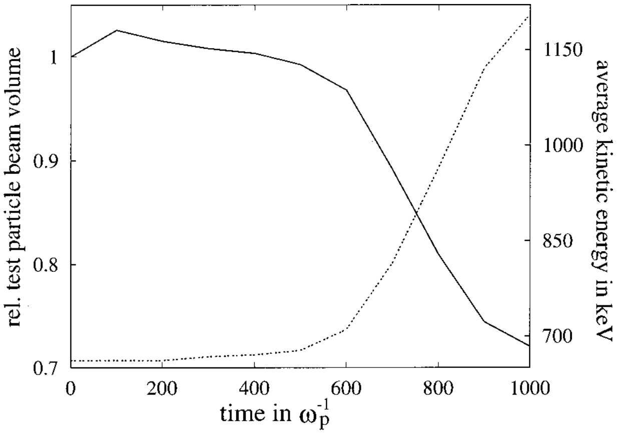

FIG. 5. The volume occupied by the beam of test particles normalized to its original volume (solid line) and the average test particles' kinetic energy (dashed line) as a function of time. The strong acceleration between $600/\omega_p$ and $900/\omega_p$ corresponds to an acceleration gradient of about 32 GeV/m for a laser wavelength of 800 nm. Initial defocusing at the channel entrance (0 to $100/\omega_p$) is followed by spatial focusing of the beam of test particles.

It appears then that this system may be a promising way of accelerating electrons to high energy, though there are various practical questions, like how to get the pulse into the tube in an efficient way, which we have not addressed. Potentially it could have advantages over other plasma based acceleration schemes. Since the pulse propagates in a tube, its velocity and the phasing of the accelerating potential ramp should be controllable. Also, it should be possible, in principle at least, to taper the tube in such a way that the pulse velocity increases along the tube. If correctly managed this could prevent the accelerated electrons from outrunning the potential ramp and lead to more effective acceleration. Also, since the pulse is not propagating in a pre-formed plasma it will be possible to make its velocity as close to c as we wish. In a beat wave or wake field scheme, the accelerating field is in resonance with a particle whose relativistic factor is

$$\gamma = \frac{\omega}{\omega_p}.$$

Very high energy particles thus require very underdense plasmas which, as the maximum field scales roughly as $\sqrt{n_e}$, will be less effective in accelerating particles. We conclude then that this is a scheme worthy of consideration as a plasma based accelerator, its possible advantages being better controllability than other schemes, since the velocity of the accelerating potential ramp depends on propagation in a solid tube rather than a plasma, and the fact that the accelerating field may remain large even when the particles are highly relativistic.

ACKNOWLEDGMENT

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