SIMULATION OF PREACCELERATED PARTICLES IN THE PLASMA BEATWAVE ACCELERATOR

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Abstract

One-dimensional relativistic and electromagnetic simulations show the Plasma Beatwave Accelerator to be a viable approach to obtaining large accelerating fields. The plasma wave excited by Raman Forward Scattering has a longitudinal electric field on the order of 100 MeV/cm to 10 GeV/cm based on plasma densities of 10^{16} cm^{-3} to 10^{20} cm^{-3}. The use of optical mixing to grow a plasma wave of the proper frequency above the noise level greatly reduces the laser intensity needed to drive the Raman instability. TeV energies for plasma electrons or preaccelerated charged particles in short distances appear feasible. Results where an injected electron beam is accelerated coherently from 1 MeV to 20 MeV in one millimeter are presented. Two- and three-dimensional effects must still be resolved.

Introduction

Intense laser beams are capable of producing transverse electromagnetic fields as high as 10^{8}-10^{10} Volts/cm. The Plasma Beatwave Accelerator[1,2] is one of a number of particle accelerator concepts utilizing the high fields inherent in intense laser beams. In this case, EM waves interact nonlinearly with an underdense plasma through optical mixing or Raman Forward Scattering (RFS) to excite large amplitude plasma waves. The plasma self-fields provide the acceleration. Thus, the concept is a collective effect accelerator. The longitudinal electrostatic field of the plasma depends on the plasma density and is typically on the order of $mc\omega_p/e$, where m is the electron rest mass, e is the electron charge, c is the speed of light and ω_p is the electron plasma frequency. For a 10^{18} cm^{-3} plasma this expression is equal to 1 GeV/cm. It explains the very high accelerating fields obtainable with this mechanism.

Because previous papers,[3-6] cover the theory in detail, we will immediately discuss the simulations. Our results address optical mixing, Raman Forward Scattering, wave synchronism, streaming instabilities and frequency matching. Only the wave-wave processes will be reviewed here. A simulation which coinjects an electron beam with the laser pulse will be described in detail.

Simulations

Simulations were carried out using a two-dimensional, fully relativistic and electromagnetic particle-in-cell code. The code can solve self-consistently for the time dependent trajectories of tens of thousand of plasma particles over thousands of plasma periods. All variables are expressed in dimensionless terms. Therefore, length is in units of c/ω_p; time is measured in units of ω_p^{-1}; and particle velocity is given by $v_i = \beta_i\gamma$ (i = 1, 2, 3), where ω_p is the initial electron plasma frequency.

In simulations on the Beatwave Accelerator two plane-polarized electromagnetic waves are launched into a Cartesian geometry. Periodic boundary conditions in the transverse (y) direction make configuration space effectively one-dimensional. In general, the simulation has 1250 cells in the longitudinal (z) direction modelling a length of 100 c/ω_p. The cells in the y direction appeared uniform because of periodicity. Each of these macrocells initially contained 24 particles. The risetime of the laser pulses was typically 25 ω_p^{-1}. The ions were taken to be an infinitely massive neutralizing background except in one run. Different simulations were made in which the values of ω_0/ω_p, ω_1/ω_p, E_0 and electron temperature, T_e, were varied where ω_0 and ω_1 are the two laser frequencies.

Usually, a vacuum region of 10π c/ω_p long was left between the left hand boundary and the plasma in order to accurately determine the dynamics of laser injection into the plasma. When the laser pulse encounters the plasma, the nonlinear ponderomotive force resulting from the intensity gradient causes the electrons to snowplow. This continues until the force arising from charge separation is greater than the ponderomotive force, and the electrons attempt to restore the charge imbalance by moving in the negative z direction. This motion initiates a train of large amplitude plasma waves.

The one drawback evident in the single wavepacket scheme[1,5] was the short pulse ($\tau < 2\pi\ \omega_p^{-1}$). This implied an instantaneous risetime to very high intensities. It is obviously unattainable. The beatwave approach, on the other hand, is a practical means of obtaining the required intensity gradient necessary for the nonlinear ponderomotive force to establish large amplitude plasma waves. The beatwave results from two parallel coherent EM sources ω_0 and ω_1 where $\omega_0 - \omega_1 = \omega_p$. This can be accomplished by utilizing two separate colinear lasers or exciting two appropriate bands of the same laser.[3]

Nonlinear Wave-Wave Processes

An alternative method of depicting the beatwave acceleration is in terms of two nonlinear wave-wave interactions. At low intensities where $E_0\ (0,1) \ll mc\omega\ (0,1)/e$ optical mixing can result in large amplitude plasma waves.[7,8] This occurs provided $\omega_p = \omega_0 \pm \omega_1$. Then, the beat frequency of the electromagnetic waves is in resonance with the plasma, and electron density fluctuations can grow. The result is linear growth of the plasma wave amplitude in time until relativistic plasma effects cause a frequency mismatch and wave saturation.

The second interaction is the Forward Raman Scattering Instability.[1,2,9] As the laser waves transit the plasma, they undergo successive scatterings where $\omega_n = \omega_0 - n\omega_p$. Alternatively, this may be viewed as $k_n = k_0 - nk_p$. This is a parametric three-wave process where a large electromagnetic wave interacts with a plasma to generate another forward moving electromagnetic wave and a plasma wave. Conservation of energy and momentum require the frequency and wavenumber matching conditions noted above. As is usual for parametric processes, the pump wave must exceed a certain intensity threshold for the instability to take place.[10]

The two wave-wave interactions, however, are not mutually exclusive - one limited to low intensities and the other to high. Rather, the plasma wave excited by optical mixing helps drive the parametric instability. To examine this a simulation with v_{osc}

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$(0,1)/c \equiv eE_0(0,1)/mc\omega(0,1) = .04$ and .05 was conducted. The plasma was cold at $\omega_p\tau = 0$. The linear growth of the plasma wave is depicted in Figure 1. At this time ($\omega_p\tau = 150$) the density fluctuations are 10% of the initial density. The analytical equation[8] indicates saturation should occur at a fluctuation level of 5%. Indeed, time histories of the laser fields indicate a cascade to lower frequencies in steps of ω_p indicative of an RFS instability. By $\omega_p\tau = 300$ the plasma field amplitude has saturated at .2 $mc\omega_p/e$, the density variations are as high as .75 of the initial value, and the RFS instability is fully developed. However, as expected, these field levels are not sufficient to trap plasma electrons at rest.

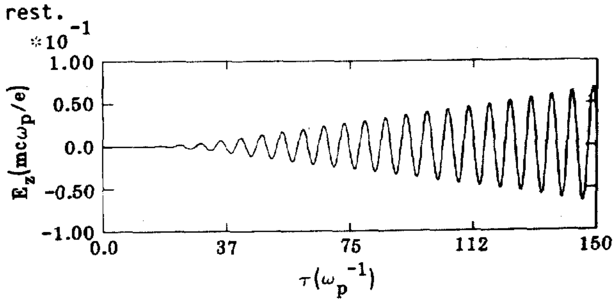

Fig. 1. Time history inside the plasma of the longitudinal electric field. Simulation parameters are ω_0=5.0 ω_p, ω_1=4.0ω_p and $E_0(0,1)$=0.2 $mc\omega_p/e$.

The importance of this result must be stressed. It indicates that large amplitude plasma waves can be grown from relatively low intensity laser sources, due to RFS excitation by optical mixing. Consider the cold plasma simulation just discussed. If ω_0 is 2.36×10^{14} sec^{-1} (λ_0=10 μm), then λ_1 is 8 μm and the plasma density is 7×10^{17} cm^{-3}. The equivalent laser intensity is only 1.3×10^{14} W/cm^2, yet the plasma wave accelerating field is 166 MeV/cm.

This lower intensity makes the Plasma Beatwave Accelerator an extremely attractive candidate for application to high energy physics accelerators. The lower intensity implies the focal spot size may be larger, thus lessening diffraction of the laser pulse in the plasma. The fact that plasma electrons are not trapped is advantageous for injection of preaccelerated, bunched particles. As has been shown in other work[6], large numbers of trapped particles lead to wave damping and loss of synchronism.

At higher intensities the RFS instability grows exponentially to a saturation level. Figure 2 depicts the plasma wave amplitude and spectrum for the case of v_{osc} (0,1)/c ~ 0.5. Note the presence of spectral components at $\omega = \omega_0 + \omega_1$ as well as $\omega = \omega_0 - \omega_1 = \omega_p$ and higher harmonics. Graphic evidence of this instability is also given in Figure 3, which is the time history and power spectra of the laser waves inside the plasma. This downward cascade of energy into multiples of ω_p is a clear signature of Raman instability. The upward cascade is the result of multiple four-wave interactions in which each wave is coupled to all other waves in a multiwave parametric process.[11] The sidebands are often referred to as Stokes (downshifted) and Anti-Stokes (upshifted) lines.

This simulation is particularly interesting, because the parameters model a CO_2 laser emitting in the 9.6 μm and 10.6 μm bands at a combined intensity of 1.3×10^{16} W/cm^2. The laser pulse is incident on a hot 10^{17} cm^{-3} plasma. Excitation of these CO_2 lines at this intensity and production of such a plasma is not beyond current technology. The higher saturation level of the electrostatic field is only a factor of

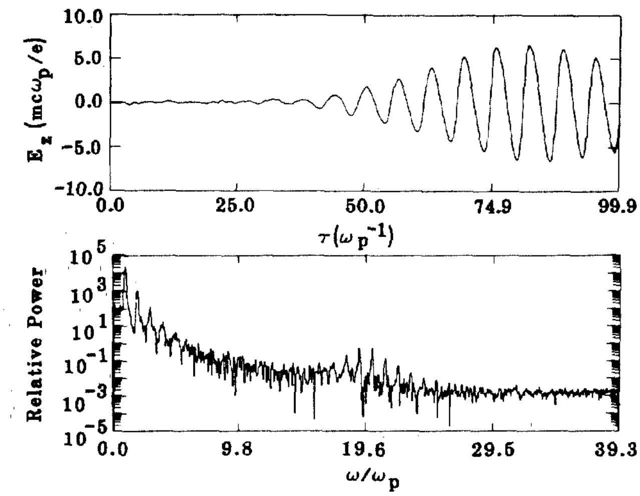

Fig. 2. Time history and the power spectrum inside the plasma of the longitudinal electric field. Simulation parameters are ω_p=10.6 ω_p, ω_1=9.6 ω_p and $E_0(0,1)$=5.0 $mc\omega_p/e$.

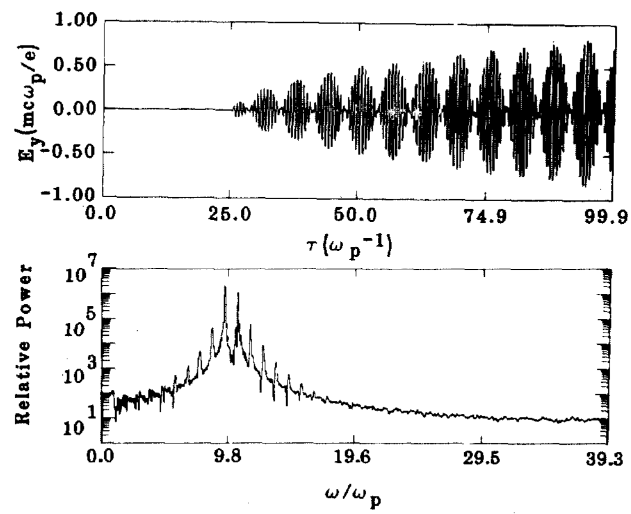

Fig. 3. Time history and the power spectrum inside the plasma of the two plane polarized laser wave electric fields. Parameters are ω_0=10.6 ω_p, ω_1=9.6ω_p and $E_0(0,1)$=5.0 $mc\omega_p/e$.

three larger in this simulation than in the run where optical mixing was important. This implies a field of 188 MeV/cm based on the lower plasma density. The combined laser intensities here, however, are equivalently 100 times larger. Nevertheless, there are some advantages to this higher intensity.

The high value of v_{osc}/c and its associated relativistic effects lead to particle trapping and acceleration of a small number of electrons. This also occurs if $T_e = 0$ for the same parameters. The trapped particles originate at wavelength intervals where $\beta_y\gamma$ is a maximum and are not associated with any overall temperature. These results are important if the plasma is to be the source of accelerated particles. In addition, the particle bunching at higher intensity is more pronounced and coherent. As a reference, assume the focal spot size for the laser pulse described above is 10^{-4} cm^2. Then, based on simulation results, a particle pulse occurs every .18 psec, contains 5×10^{10} electrons, carries a peak current of 96 kA at a current density of 960 Megamps/cm^2. The main reason for belaboring this point is to indicate the potential the plasma has for confining and accelerating high density bunches of preaccelerated ions.

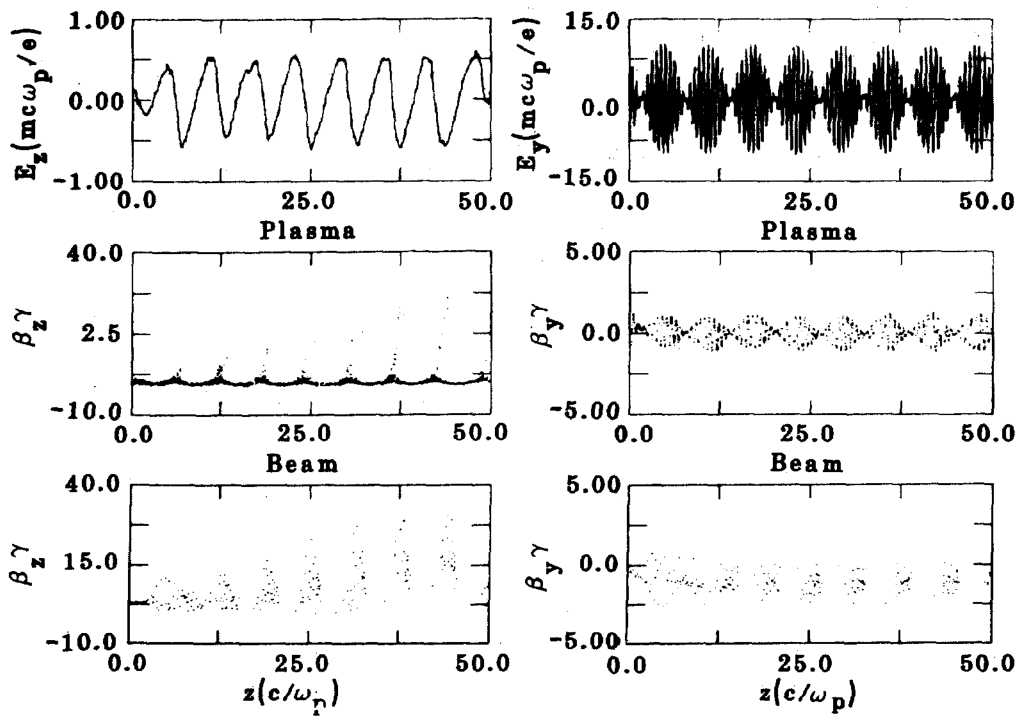

Fig. 4. Plots of a) plasma wave electric field, b) laser electric field, c) plasma electron longitudinal, d) plasma electron transverse, e) beam longitudinal, and f) beam transverse momentum phase spaces at $\omega_p\tau = 74.0$. Simulation parameters are ω_0=10.6 ω_p, ω_1=9.6 ω_p, $E_0(0,1)$ = 5.0 $mc\omega_p/e$ and T_e = 0 keV.

A 1 MeV electron beam with a density of 10^{14} cm^{-3} was coinjected with a 10^{16} W/cm CO_2 laser emitting at 10.6 µm and 9.6 µm. Thus, the beam to plasma density ratio was .001. The plasma was cold. As before, a small number of plasma electrons are trapped and accelerated resulting in a monotonically decreasing distribution. Because the electron beam was not bunched at injection, its accelerated emittance is large. Notably, the beam particles bunch at a phase in the wave which is different from the plasma electron bunches. Yet no streaming instability results. Plots of various quantities of interest are given in Figure 4. The total longitudinal distance is 0.8 mm for the given plasma density. A more conclusive test using prebunched, monoenergetic ions at a laser intensity which does not allow plasma trapping is needed. If this indicates a problem, we will lower the ratio of beam to plasma densities to determine at what point the growth is negligible. These studies will also address emittance growth. Both issues will help establish the expected beam luminosity as it exits the accelerator.

Acknowledgement

This work was supported by the Air Force Weapons Laboratory. The author is pleased to acknowledge many useful discussions with Drs. B. Godfrey, C. Joshi, A. Sessler, T. Tajima and W. Willis.

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