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A PLASMA WAVE ACCELERATOR - SURFATRON II

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Introduction

With the advent of high power lasers it has become possible to generate fast large-amplitude electrostatic waves in a plasma. These waves have been the basis for several accelerator schemes.[1] Inherent in all these schemes is the limitation that the particles eventually outrun the wave. Therefore, although the plasma wave has an enormous electric field, the particles only interact with the field for a limited length of time. Straight-forward calculations show that in either the wake plasmon or the beat wave accelerator schemes the maximum obtainable energy is $2(\omega/\omega_p)^2mc^2$ and that this energy is obtained in a time which is roughly $2(\omega/\omega_p)^2 1/\omega_p$. Here ω represents the incoming laser frequency and ω_p represents the plasma frequency.[1,2] In this and the accompanying paper, hereafter referred to as I, theory and computer simulations are presented which demonstrate that, when a magnetic field is inserted perpendicular to the direction of wave propagation, the particles remain in phase with the wave.[3] In principle particles can, therefore, aquire unlimited amounts of energy.

In the accelerator schemes briefly alluded to above, the analysis can be divided into two parts. One first studies the generation of the plasma wave, which is driven by the non-linear interaction between the incoming laser and the plasma and, second, the dynamics of a single particle in the plasma wave. A magnetic field will affect the propagation properties of the plasma wave if $\omega_c \gtrsim \omega_p$ where ω_c is the cyclotron frequency. However, it is shown in paper I that in order for the particles to remain trapped the electric field must be larger than γ_{ph} times the magnetic field where γ_{ph} is $(1 - v_{ph}^2/c^2)^{-\frac{1}{2}}$ and v_{ph} is the phase velocity of the plasma wave. The electric field is proportional to the plasma frequency so that in order for the trapping inequality to be satisfied ω_p/ω_c must be larger than 1. Therefore, for magnetic fields pertinent to the accelerator mechanism which is being presented, the generation of plasma waves is essentially unchanged.[4] So the analytical discussion in I concerns itself solely with the motion of a single particle in a cross magnetic field. In this paper the results of computer simulations, which are shown to be in agreement with scaling laws obtained in I, are presented.

Simulations

To demonstrate that the insertion of a magnetic field does indeed lead to particles with higher energies, computer simulations employing a 1-2/2 D relativistic electromagnetic particle code were conducted. Runs were carried out both with and without the magnetic field and the results were then compared in order to elucidate the differences. Typically, runs were carried out on a system comprised of 1024 grids. In simulations all units are dimensionless. For example, time is in units of ω_p^{-1} and distance is in units of v_{th}/ω_p. The method for exciting the plasma waves was chosen to be optical mixing. The field geometry for the simulations was the following. For runs without the magnetic field two light waves with frequencies $4\omega_p$ and $5\omega_p$ were launched into the plasma from the left hand x-axis boundary. The laser electric field was polarized in the y direction. For runs with the magnetic field, a uniform magnetic field was inserted in the y direction. In both runs the electromagnetic waves were absorbed as they left the system and the particles were readmitted with the thermal velocity. The lasers reached maximum intensities which correspond to a $v_{os}/c \sim .4$ with rise times τ of 120 ω_p^{-1}. The plasma temperature was 5 keV, while the value of the magnetic field was chosen so that $\omega_p/\omega_c = 8$. In simulation units this means that $c = 8$ and $\omega_c = 1/8$. Thus, for a CO_2 laser with wavelengths 10.6 μm and 9.6 μm the parameters were $B \sim 300$ kG, $I \sim 2\times10^{15}$ W/cm^2, $n_e \sim 6.25\times10^{17}$/cm^3, and $\tau \sim 2.7$ ps.

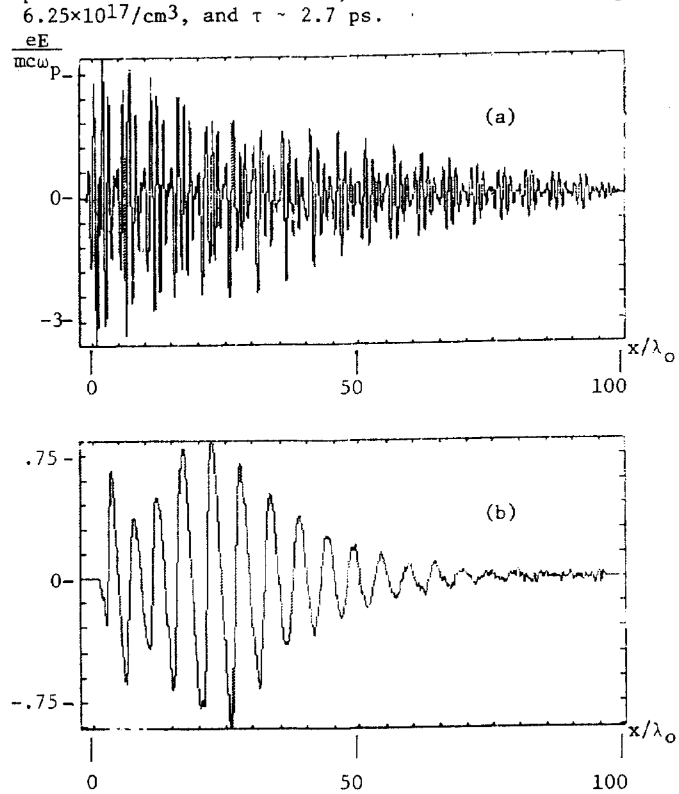

Figure 1 Plots of a) the laser electric field and b) the longitudinal field vs. x in a run with the magnetic field at $t = 120\ \omega_p^{-1}$. The fields are in units of $(mc\omega_p/e)$ and x is in units of the wavelength, λ_o of the highest frequency laser.

In Figure 1 the transverse and longitudinal electric fields are plotted vs. x in a run with a magnetic field at $t = 120\ \omega_p^{-1}$. The transverse field is propagating from left to right. It is evident that the longitudinal wave is being driven at a wavelength which corresponds to the long wavelength structure of the transverse field. The longitudinal field is approaching values ~ .75 of the cold plasma wave-breaking value $mc\omega_p/e$. For a CO_2 laser this corresponds to an electric field of ~ 55 GeV/m. Although they are not shown, the corresponding plots for the run without the magnetic field are very similar. The magnetic field as expected did not influence the generation of the plasma wave.

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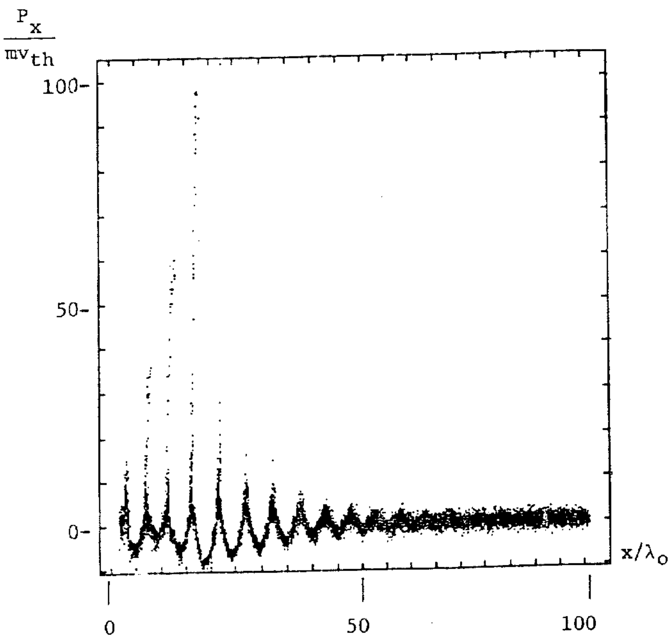

Figure 2 Plot of electron phase space along the x-direction in a run with the magnetic field at $t = 120\ \omega_p^{-1}$. P_x is in units of mv_{th}.

In a run with the magnetic field the phase space of the electrons is plotted in Figure 2 at $t = 120\ \omega_p^{-1}$. The momentum axis is plotted in units of mv_{th}. The trapped particles are clearly seen as they extend way above the bulk distribution. At this early time a correspondence between the longitudinal electric field and the positions of the trapped particles are clearly seen. For large P_x, $\gamma \sim P_x/c$, so the maximum γ is around 13. In addition, when the magnetic field is not present the electrons at this early time have γ's which are about the same magnitude.

In order to demonstrate the most important improvement that the transverse magnetic field provides plots of P_x vs. x for the electrons are now shown at a later time $t = 210\ \omega_p^{-1}$ in Figure 3. Whereas before at $t = 120\ \omega_p^{-1}$ the most energetic particles with and without the B field had approximately the same energies, now at $t = 210\ \omega_p^{-1}$ the particles for the run with the magnetic field have substantially higher γ's. This is true even though in the run without the magnetic field the trapped particles are further along in the system. This brings up the fact that in the run without the magnetic field there was only one "arm" of very energetic particles, while with the magnetic field several "arms" of very energetic particles were formed. The main point of this discussion is that without the magnetic field the particles are now outrunning the wave while with the magnetic field the particles are phase locked to the wave. Indeed, if the particles had seen a constant electric field of amplitude γ_{ph} B, then an expression for $\gamma(x) = \gamma_{ph}\omega_c x/c$ could be written down immediately. A more detailed discussion is given in paper I. For $\Delta x \sim 625$, γ should be ~ 40, and the simulation shows a value slightly larger than this. Any discrepancy can be attributed to the fact that the Δx used is an approximate value. In any case, this gives credence to the idea that the particles are phase locked to the wave. It should also be noticed that the plasma is heating up to temperatures of 100's of keV in the back of the laser. This is consistent with the simulations done by others.[1,4]

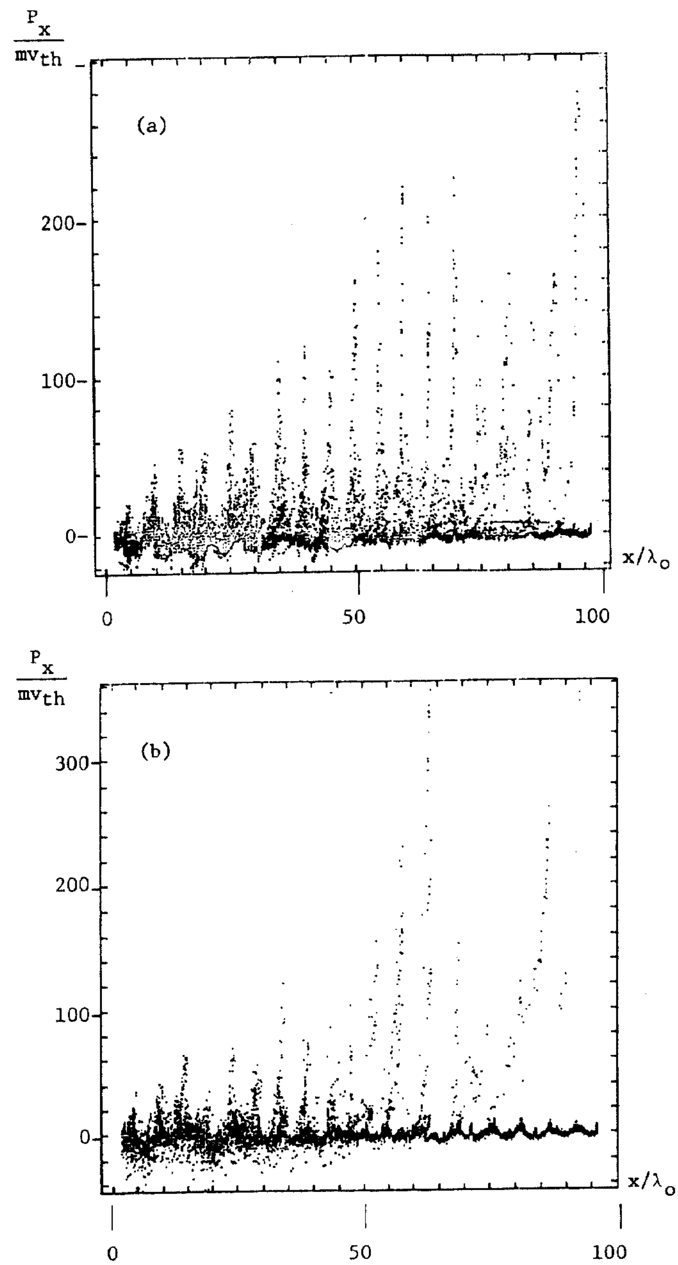

Figure 3 Plots of the electron phase space along the x-direction for run a) without a magnetic field and b) with a magnetic field at t = $t = 210\ \omega_p^{-1}$.

Figure 4a shows a plot of P_z vs. x for a run with the B field. The maximum value of P_z is a very linear function of x with a slope of $\sim .12$. We now compare this to the value predicted by the expression given in I, $P_z = qBx/c$, which for simulation units is $P_z = x\omega_c$. In our runs $\omega_c = 1/8$, so the theory would predict a slope of .125. Thus the results from the simulation are in excellent agreement with the analytical expression. In Figure 4b, a plot of P_z vs. P_x is given. The point to note here is that the particles travel down the system with a well defined ratio of $P_z/P_x = v_z/v_x$. This ratio can be obtained by noting that, while the particles' total velocity is c, its x velocity is v_{ph} because it is trapped. Hence, $v_z^2 =$

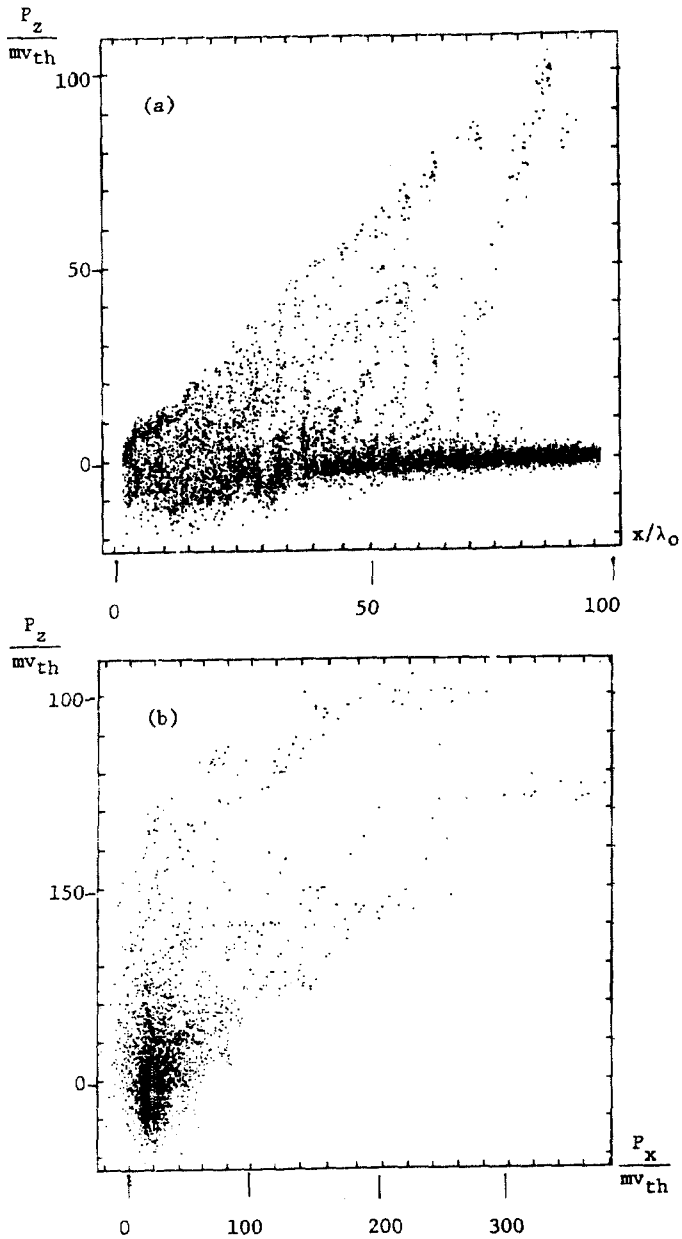

Figure 4 Plots of a) the electron phase space in the z direction and b) P_z vs. P_x for a run with a magnetic field at $t = 210\ \omega_p^{-1}$.

$c^2 - v_{ph}^2 = c^2/\gamma_{ph}^2$. Since $v_{ph} \sim c$, it follows that $P_z/P_x = v_z/v_x \sim 1/\gamma_{ph} = \omega_p/\omega$. From Figure 4b, $P_x/P_z \sim 4$, which compares favorably to the analytical value of γ_{ph} which for the run presented is between 4 and 5. This well defined ratio v_z/v_x offers a possible diagnostic tool for an experiment designed to test the mechanism since the energetic particles would leave the system at an angle relative to the axis of the laser. For the run presented this angle is $\sim 14^o$.

Conclusion

We have shown that the insertion of a cross magnetic field prevents the particles from getting out of phase with the electric field of the plasma wave in the beat wave accelerator scheme. Thus, using a CO_2 laser, $n_c/n_e = (\omega_o/\omega_p)^2 \sim 35$, and a 300 kG magnetic field, electrons can be (in principle) accelerated to 100 GeV in 2 meters. For comparison without the magnetic field, the same energies may be obtained in a n_c/n_e 10^5 plasma over a distance of 100 meters.

The above estimate is based on an extrapolation of a 1-D simulation which was run for a relatively short time. What is obviously necessary are simulations to be carried out on a larger system, for more realistic lengths of time, to confirm the results of the 1-D simulations and single particle calculations presented in this and the accompanying paper. Also, 2-D simulations have yet to be carried out to examine the two-dimensional effects.

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