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STUDIES OF THE PLASMA DROPLET ACCELERATOR SCHEME

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SUMMARY

In the plasma droplet accelerator scheme, proposed by R. Palmer, a sequence of liquid micro-spheres generated by a jet printer are ionized by an incoming intense laser. The hope is that the micro-spheres now acting as conducting balls will allow efficient coupling of the incoming laser radiation into an accelerating mode. Motivated by this we have carried out 2D, particle simulations in order to answer some of the plasma physics questions hitherto unaddressed. In particular we find that at least for laser intensities exceeding $v_0/c=0.03$ ($\sim 10^{13}$ w/cm^2 for a CO_2 laser), the incident laser light is rather efficiently absorbed in a hot electron distribution. Up to 70% of the incident energy can be absorbed by these electrons which rapidly expand and fill the vacuum space between the microspheres with a low density plasma. These results indicate that it is advisable to stay clear of plasma formation and thus put on an upper limit on the maximum surface fields that can be tolerated in the droplet-accelerator scheme.

INTRODUCTION

Recently, R. Palmer and co-workers[1] have been investigating whether a suitable accelerating mode can be excited for relativistic particles using a periodic arrangement of micro-spheres. These micro-spheres have a radius of $\sim 0.1\lambda$ and are spaced $\lambda/2$ apart where λ is the wavelength of the radiation used to excite such a structure. For instance when a 10μm CO_2 laser is used to excite such a structure it is hoped that longitudinal fields of many GeV/m can be produced for the accelerating mode.

Rf modelling using 11 cm diameter spheres and 30 cm wavelength radiation has revealed that although a single row of such spheres does not support an accelerating mode, with two parallel rows of spheres both an accelerating and a focusing mode exists[1]. In this case the spheres act as dipoles oscillating in the plane of the double row, 180° out of phase, and therefore particles can be accelerated along the axis in between the two rows. To couple the radiation from an external source such as a laser, the double row structure has to be perturbed. It has been shown by Palmer, et al.[1], that if alternate spheres are slightly lifted or depressed from the plane in which they initially lay, such perturbations can couple the accelerating mode to radiation propagating either upward or downward perpendicular to the plane containing the spheres (Fig. 1). The maximum limit on the accelerating field in the droplet accelerator is given by the intensity of the laser field and the Q of the cavity.

As the laser intensity is increased, the spheres will at some stage ionize and form a plasma. If extremely short laser pulses on the order of tens of laser cycles are used then the ions will not have any time to move. The hope is that the plasma which is highly conducting will allow efficient coupling of the laser light to the desired mode as though the balls were tiny conducting solid spheres. A simple estimate indicates that when the quiver energy of the electrons $1/2\ mV_0^2$ (where $V_0 \sim eE/m\omega$, E is the laser field and ω the laser frequency) exceeds the ionization energy, the surface atoms will ionize and form a plasma. For a CO_2 laser this implies laser intensities exceeding $\sim 2 \times 10^{11}$ w/cm^2. Once the electron density exceeds the critical density where $\omega = \omega_p$ strong laser coupling to the plasma may be expected. For a CO_2 laser the critical density is 10^{19} electrons/cm^3, only 10^{-4} of the solid density.

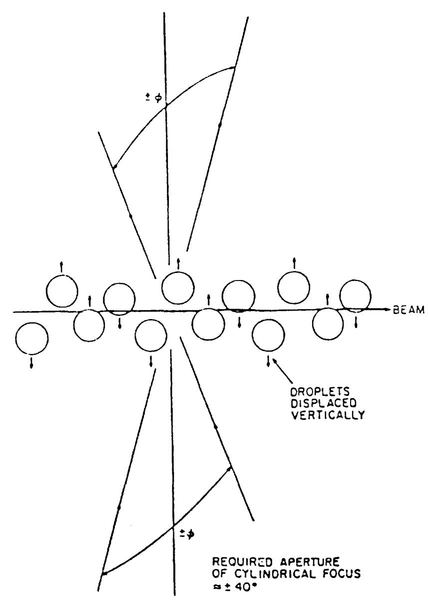

Figure 1. The laser-droplet configuration.

Motivated by this we have carried out 2D, particle simulations in order to answer some of the plasma physics issues which may play an important role in this scheme.

INTRODUCTION TO SIMULATIONS

For the simulations we used the two-dimensional particle-in-cell code WAVE[2]. To model the coupling of the incoming laser to the accelerating mode for the laser droplet configuration described in part I requires three dimensions. Therefore, we are unable to investigate the coupling efficiency with our particle code. However, we are able to study the absorption of the laser by the droplets and the concomitant energetic electron production. In particular we irradiated columns of plasma rods (geometric analogy of spheres in two dimensions). Each rod consisted of either 10,000 or 40,000 simulation electrons and ions. For reasons given in part I, the rods radii were $\lambda_0/10$ and the rods centers were separated by $\lambda_0/2$ where λ_0 is the laser's vacuum wavelength. Both one and two columns of rods were irradiated. The later case is depicted in Figure 2a where a particle plot at t=0 from one simulation is shown. The simulation box was typically 128 cells x 128 cells which corresponds to λ_o x λ_o in physical units. Each rod has a constant density which rises from 0 to 10nc in one cell. The critical density, nc, is defined as the density where the light frequency ω_o is equal to the plasma frequency $\sqrt{4\pi e^2 n/m}$. In this way, since light does not penetrate past the critical surface, the rods act like solid pellets. The laser's V_o/c was either .1 or .035 which can be converted to intensity by the convenient formula $I = 1.3 \times 10^{18}\ (V_o/c)^2/\lambda_\mu^2$ where I is in units of Watts/cm^2 and λ_μ is in units of microns. The laser has a rise time of $50\omega_o^{-1}$ and the simulations generally last 150 ω_o^{-1}. For CO_2 parameters 150 ω_o^{-1} corresponds to .8ps. The plasma rods were typically initiated with a temperature of 1 KeV for both the electrons and ions.

Before proceeding to the results we mention some limitations of the simulations. As previously noted, the two dimensionality of the simulations prevents a study of the coupling between the incoming laser to the accelerating mode. In addition, the rods are already fully ionized. Therefore, all self-consistent effects associated with the ionization processes have been ignored. Also, since rods are fully ionized, electrons can flow through them unimpeded. This may be realistic since the energetic electrons observed in the simulations will have mean free paths greater than the droplet's diameter. Another limitation is that because the simulation box is periodic in y and its y dimension is typically on the order of λ_o any diffraction and reflection at oblique angles will be altered since these modes have $k_\perp$'s that will not fit exactly into the box. We carried out two sets of simulations with this last limitation in mind. In one, the box was λ_o x λ_o; while in the other, the box box was λ_o x 4 λ_o. In terms of absorption and reflection there was little variation between the two sets. Thus, we acknowledge the limitation but we are not concerned by it.

RESULTS

It is well known in plasma physics that radiation impinging obliquely on a plasma with a density gradient may be substantially absorbed at the point where $\omega_o = \omega_p$ by a linear mode conversion process called resonant absorption[3,4,5]. The resulting electric field pattern can preferentially accelerate electrons down the density gradient. This process has been studied in great detail because of its importance to ionospheric physics and hot electron generation in laser fusion.

There are several scale lengths important to the resonant absorption problem[4]. Those relevant to our simulations are: 1) the scale length at the droplet peak density, L, 2) the lasers wavelength $\lambda_o = 2\pi/k_o$, and 3) a typical electron excursion length, which could either be the debye length at peak density $\lambda d \equiv V_{th}/\omega$ or the excursion in the local electric field, V_E/ω_o. For the steep gradient condition presented here, $k_oL \sim .05 << 1$, previous fluid theory and particle computer simulations[4,5,6,7] have still shown substantial absorption from resonance absorption. Furthermore, in this limit, higher absorption levels are possible through a highly non-linear form of resonance absorption involving waves[7] and through a process called the anomolous skin effect[8]. When the excursion distance is on the order of L, the resonance is broadened by dispersion and the ambipolar potential becomes important.

In our opinion the major threat that absorption poses to the droplet scheme is that the heated electrons flow into the vacuum region between the plasma rods. The plasma density surrounding the droplets falls from liquid density to 0. Therefore if only a small percentage of this plasma fills the vacuum region the plasma density (predominantly electrons since the ions do not mvove as fast) in the accelerating structure can still be appreciable. The ensuing coupling between the incoming radiation and the accelerating mode could be profoundly affected if this happens. All this is demonstrated in figures 2 and 3. In figure 2b a particle plot of the electrons from a simulation where the rods consist of an electron proton plasma at t = 150 ω_o^{-1} is presented.

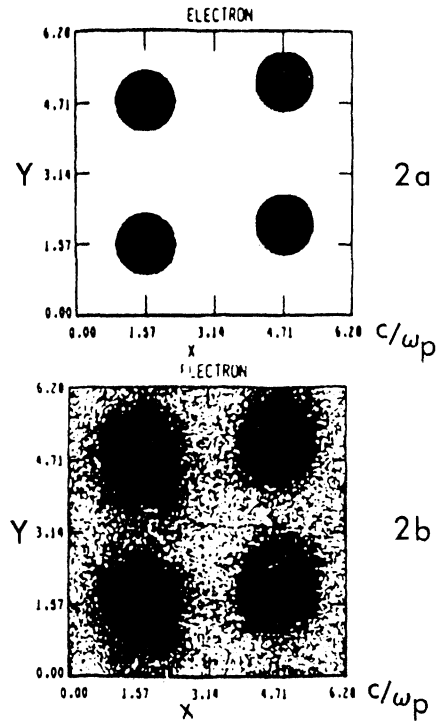

Figure 2. An electron particle plot at a) $t=o\omega_o^{-1}$ and b) $t=150\omega_o^{-1}$.

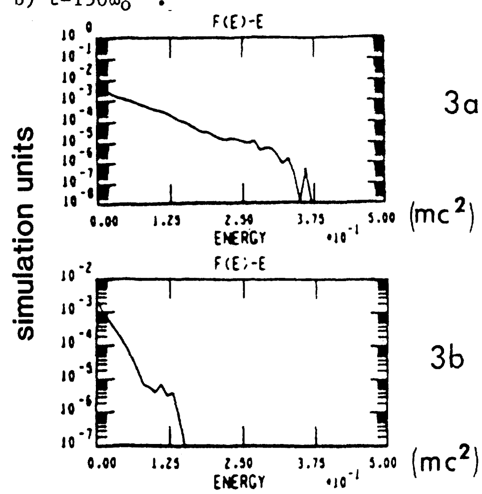

Figure 3. Energetic electron distribution function.

When compared to figure 2a which is the same type of plot at t = 0 it is clear that a significant number of electrons are entering the space between the rods. The temperature of those electrons in the vacuum regions (T_h) is monitored by measuring the energy spectrum of the electrons, striking the right and left hand boundaries. This distribution function is plotted in figure 3 where parts a and b were taken from a simulation in which V_o/c = .1 and .035 respectively. T_h is estimated as 18 KeV in fig. 2a and 8 KeV in fig. 2b.

We also did some fixed ion simulations to clearly identify the role that ions play. The parameters were otherwise identical to the V_o/c=l simulations. The measured T_h was the same, although there were fewer energetic electrons. In anticipation that in the plasma droplet scheme the initial temperature, Tc, may be lower than 1 keV, we carried out one low intensity, V_o/c=.035 and low temperature, T_c=250 ev, simulation. We found that, surprisingly, the eventual T_h was the same. However, the important point is that even at these lower temperatures, a significant number of electrons entered the vacuum region.

Interestingly, the above temperature scale as $(Vo/c)^{1/3}$, which is the scaling found in earlier resonance absorption studies[5,6]. Although at present we believe this agreement is coincidential. In our simulations, evidence of resonance absorption was the observation of radiation leaving the simulation box at the second and third harmonic of the incoming laser. This has previously been determined to be a reliable diagnostic resonance absorption in steep gradients from experiment, computer simulation[9], and theory[10].

Up till now we have concentrated on the hot electron generation rather than absorption. Absorption can be important if a substantial amount of laser energy is absorbed before it can couple into the accelerating mode. To measure the absorption we monitor the Poynting flux in the x direction. This plot is shown in figure 4 for two cases.

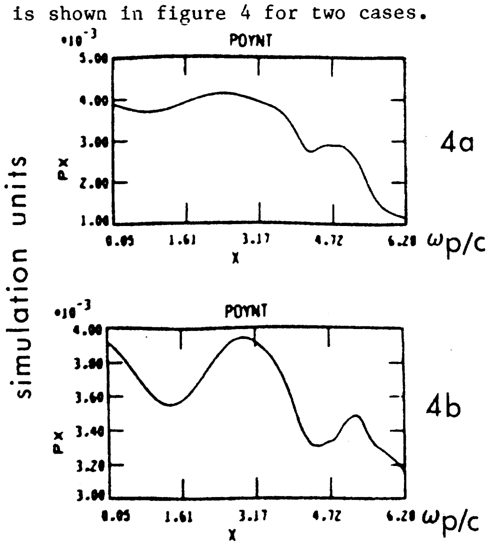

Figure 4. The poynting flux as a function of X.

In Fig. 4a the x component of the Poynting vector is shown at t= 150 ω_0^{-1} from a simulation in which a single column of two rods was illuminated by a laser with V_o/c=0.1. As seen, approximately 70% of the incoming radiation is absorbed. This is consistent with the two columns simulations with two columns of rods where 70% absorption occurs across the first column and 90% across both columns. In Fig. 4b the same plot is shown from a fixed ion simulation. Whereas the hot electron temperature, T_h, did not differ between the fixed ion and the mobile ion case, the absorption is profoundly different. The absorption with fixed ions is constant in time near 15%. This compares favorably to the early times in the mobile ion case. At late times, however, the absorption approaches 70%. This difference is consistent with the earlier observation that although the T_h's are comparable more electrons are heated in the mobile ion case. Evidently, only a slight expansion of the ions is necessary to alter the absorption.

The absorption increased slightly to 80% when the laser's intensity was decreased to Vo/c=.035. Furthermore, absorption levels approaching 60% were obtained at late times, t=190 ω_o^{-1}, in the T_c=250 ev simulation. Although, at earlier times, t=100 ω_o^{-1} the absorption levels resembled those from the fixed ion case. The implication is that the absorption is relatively unaffected as either T_c or V_o/c are lowered. This differs from the T_h scaling given above.

We determined that the absorbed energy manifests itself predominantly in energetic electrons by monitoring the change in time of both the field energy and kinetic energy. This does not mean, however, that energy is not present in surface waves. We note without presenting our supporting evidence that surface waves with a transverse mode number determined by the spacing of the rods is present in all of our simulations.

CONCLUSION

In conclusion, we have shown that when a plasma forms on the edge of the droplets absorption levels of the incoming radiation above 30% may occur in a time as short as 150 ω_o^{-1}. Furthermore, concomitant with the absorption is the production of energetic electrons which fill the vacuum region between the droplets even before appreciable absorption. On the basis of these simulations, therefore, it would appear that the maximum tolerable surface fields (laser and/or cavity modes) in the droplet accelerator scheme will be below the plasma formation threshold even.

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