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**RAMAN SCATTERING AND
ASSOCIATED FAST ELECTRON PRODUCTION****DOE FINAL TECHNICAL REPORT****R.D. Brooks and Z.A. Pietrzyk****April 16, 1984 - April 15, 1985****UWAERP/6****Issued: August 1985**

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ABSTRACT

High energy electrons in plasmas have been attributed to various causes including trapping by electron plasma waves created by stimulated Raman scattering. A theory, consistent with experimental results, based on the acceleration of trapped electrons by such electron plasma waves as they propagate in the presence of a density gradient away from the region where they are created is presented. Single particle simulations show accelerating voltages as high as 20 GV/m.

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I. INTRODUCTION

This report describes work performed at the University of Washington in support of the inertial confinement fusion program funded by the U.S. Department of Energy (Contract #529 26 05).

High energy electrons have been present and observed in many laser-plasma interaction experiments.^{1,2} Though there are several mechanisms to accelerate electrons in a plasma, in this paper the discussion will be limited to electron acceleration by plasma waves, especially those generated by laser-plasma interaction. Particular attention will be paid to the acceleration of electrons from a very low energy (low temperature plasma) and the effect of changing plasma parameters on the subsequent acceleration of an electron by an electron plasma wave as it propagates away from the region where the driving process created it.

High energy electrons are very detrimental to inertial fusion³ as they can preheat the center of the pellet thus preventing high compression. On the other hand, electron acceleration by plasma waves has been proposed as a means of accelerating electrons to very high energies in short distances in the next generation of electron accelerators.^{4,5} Strong plasma waves can be generated a number of ways, including stimulated Raman scattering, the two-plasmon decay instability, and wave mixing where two laser beams with frequencies that differ by that of the plasma wave are used.⁶ Raman scattering and wave mixing are very similar; wave mixing supplying the daughter electro-magnetic wave of the Raman scattering process and thus not requiring the high driver intensity Raman scattering does to overcome damping. While wave mixing can only supply the daughter wave appropriate to a narrow density range, the Raman scattering daughter wave will adjust

itself to various plasma conditions, as long as the laser intensity is above threshold.

It will be shown that changing plasma parameters within small distances can accelerate electrons to very high energies--much higher than from regular wave mixing in a homogeneous plasma. This mechanism is believed to be responsible for the high energy electron distribution observed in the laboratory for low laser beam intensity.²

The production of fast electrons by plasma waves generated by Raman scattering has been predicted by numerical simulation.⁷ It has been isolated from other mechanisms of acceleration in several experiments.^{2,8} Simulations⁷ predict that the hot electrons will have near Maxwellian distributions with temperatures corresponding to the phase velocity of the plasma waves. No intuitive physical explanation of this result is known, as ideally one would expect most of the accelerated electrons to move with the plasma wave phase velocity for non-relativistic waves. Maxwellian distributions of hot electrons are experimentally observed, but it is difficult to know precisely what the plasma wave phase velocity is as it depends on the scattering angle. For a low laser intensity and plasma density below $1/4$ critical, only Raman backscattering is expected. The resultant plasma wave phase velocity can then be determined. The results in our laboratory² show an electron temperature commensurate with a much higher velocity. It will be shown that a probable explanation for this depends upon the well-known change in the phase velocity of an electron plasma wave as it propagates in a density gradient. It is demonstrated that under certain circumstances these waves can accelerate up a density gradient while carrying trapped electrons. This leads to the proposal of a new method of

electron acceleration by plasma waves traveling away from their point of generation.

There are several mechanisms of electron acceleration described in this paper. We begin by describing processes capable of accelerating cold electrons. Though there is a continuing interest in these processes we show that there is no need to involve nonlinear wave properties (e.g. high harmonics) to achieve effective acceleration. The next question which we address is why electrons accelerated by an electron plasma wave are not mono-energetic with the wave phase velocity, but rather have a near maxwellian distribution with a temperature commensurate with the wave's phase velocity. This question is not fully answered in the paper but we suggest that it is a result of the point at which the electrons become untrapped. This is related to so many parameters that a random distribution results. We were also interested in an explanation for the unexpectedly high electron acceleration for the relatively low laser intensity present in our experiment². This resulted in the formulation of a physical description in which the electrons are accelerated by electron plasma waves propagating in a slightly inhomogenous plasma. (For example, an electron plasma will accelerate as it propagates up a density gradient.) Using single particle simulations we show that this is consistent with our experimental results though we do not prove that this is the process responsible for the observed acceleration. A preliminary extension of these simulations reveals a possible high energy electron acceleration scenario. We believe that this scenario may be technologically impossible to achieve even if some of the theoretical restrictions, such as the parametric decay instability of the free running electron plasma wave, do not preclude its application. This acceleration process may, however, be important in other laser-plasma

interaction situations including electron plasma wave acceleration schemes such as the "surfatron." If, in such a device, the density changes by a sufficient amount to lose resonance of the beat waves, the electron plasma wave will propagate freely and be subject to the acceleration which we describe. We believe that this mechanism may result in restrictions on the plasma quality for the "surfatron" accelerator though other factors seem likely to mitigate the effect.

The density or temperature inhomogeneity effect which we describe can be observed only in special cases of laser-plasma interaction. If the laser intensity is too high a new electron plasma wave will, in effect, be created at each density. The density gradient also needs to be within a proper range. If the gradient is too small the wave will be damped or decay before a significant velocity change can result. If the gradient is too large (e.g. inertial confinement experiments) the electrons cannot be trapped as the wave accelerates much too rapidly to hold them.

II. BACKGROUND AND THEORY

A. Laser-Particle Acceleration Mechanisms

Though an intense laser beam produces a sizeable electric field it does not, in itself, offer an effective means of charged particle acceleration. This is because the electric field is oscillatory and perpendicular to the direction of propagation. What results is a "quiver" velocity superimposed on the previous velocity of the charged particle. Because of the frequencies involved, electrons can respond where ions are effectively fixed because of their greater mass. In order to achieve charged particle acceleration through the use of a laser a means has to be found to produce a longitudinal electric field or to couple the quiver velocity to the

particle's energy. A number of such mechanisms have been proposed,⁸ but only those relevant to acceleration in a plasma will be reviewed here.

Landau Damping. An electron plasma wave (EPW) can be created in a plasma by a variety of mechanisms. These waves involve the longitudinal displacement of electrons in an essentially fixed ion background. The result, for a constant density, is a periodic wave whose electric field ($B=0$) is in the direction of propagation and is given by

$$E = E_0 \sin (kx - \omega t), \quad (1)$$

where k is the electron plasma wave number, ω is its angular frequency, x is displacement, and t is time. The dispersion relation for this wave is given by

$$\omega^2 = \omega_p^2 + 3v_{th}^2 k^2, \text{ where:} \quad (2)$$

$$\omega_p \left(\frac{\text{rad}}{\text{sec}} \right) = 5.64 \times 10^4 n_e^{1/2}, \quad (3)$$

$$v_{th} \left(\frac{\text{cm}}{\text{sec}} \right) = (T_e / m_e)^{1/2} = 4.19 \times 10^7 T_e^{1/2} \quad (4)$$

and m_e , $n_e(\text{cm}^{-3})$ and $T_e(\text{eV})$ are the electron mass, density and temperature, respectively.

For a density gradient in the direction of propagation the phase velocity of the EPW will be different than for the same constant density. Though this effect is not included in the derivations here it is present in the single particle calculations.

An EPW is capable of losing energy to a particle moving slightly slower than its phase velocity ($v_\phi = \omega/k$), as the wave's electric field accelerates the particle. Similarly, particles moving slightly faster than the wave can lose energy to the wave. For a Maxwellian distribution, of course, there are more particles moving slower than the wave than faster and the wave loses energy. For a wave with a sufficiently small potential ($\phi_0 = E_0/k$) the governing equations can be linearized and the change in the velocity of a particle with initial average velocity v_0 (there will be an additional oscillatory component, v_{osc}) can be found⁹

$$\Delta v = -\left(\frac{eE_0}{m_e}\right)^2 \frac{k^2(v_0 - v_\phi)}{24} t^4, \quad (5)$$

valid for $k(v_0 - v_\phi)t \ll 1$ (i.e., short times) where t is time and e and m_e are the electron charge and mass, respectively.

Trapping. For cases where the potential of the wave is significant the equations cannot be linearized. This situation is only likely to develop when the phase velocity of the wave is well above the velocity distribution of the electrons. In this case, if the relative velocity between the particle and the wave is small enough that the particle can be accelerated this amount by the oscillatory field of the longitudinal wave during a single period, the particle will become trapped by the wave. It will then travel with a mean velocity equal to the phase velocity but will oscillate within the wave trough. The velocity difference, v_t , or the "trapping velocity" is given by⁹

$$v_{tr} = (v_{\phi} - v_0) = 2 \left(\frac{eE_0}{m_e k} \right)^{1/2} = 2(v_{osc} v_{\phi})^{1/2} \quad (6)$$

where v_{osc} is the oscillatory velocity due to the electron plasma wave of an un-trapped particle:

$$v_{osc} = \frac{eE_0}{m_e \omega} \quad (7)$$

and the particle velocity is given by

$$v = v_0 + v_{osc}$$

Thus it can be seen that a wave with a large enough potential can trap electrons with quite low velocities. In fact, some theories are based upon the wave potential growing until it reaches the cold electrons and traps them. This is called the wave breaking limit. The fact that the trapped particles have a significant bounce velocity may be undesirable if a mono-energetic beam is required from an accelerator. If, however, particles are injected with $v_0 = v_{\phi}$, little bounce velocity results.

Once a particle has been trapped in an electron plasma wave it can remain trapped as the velocity of the wave varies (increases) as long as this does not happen too quickly. This effect, the central theme of this paper, will be discussed in a separate section.

Pondermotive Force. With or without a magnetic field a charged particle subject to an oscillatory electric field with a spatial variation, e.g.,

$$E = E_0(x) \sin(\omega t) \quad (8)$$

will be accelerated towards regions of weaker field. This can be visualized when E is in the direction of x by realizing that the restoring force of the periodic motion will be stronger where $E_0(x)$ is larger. This results in a "drift" toward weaker E_0 which is superimposed on the oscillatory motion. For a transverse electric field (i.e., E in y direction) with a magnetic field the coupling to the magnetic field must be included and without the magnetic field the curvature of the electric field must be considered but the same result is obtained. The pondermotive force averaged over the wave period is given by

$$F_p = \frac{-e}{4m_e\omega} \frac{d}{dx} (E_0^2) = -\frac{m_e}{4} \frac{d}{dx} (v_q^2). \quad (9)$$

This force acts upon all electrons and is transmitted to ions through charge separation. It is responsible for laser self-focusing and other effects, but shows little promise as a particle accelerator.

Wave Growth. An often overlooked mechanism by which particles can be accelerated in a plasma is due to the temporal growth of a wave. This growth results in an increase in v_{osc} with time. Though an analytical solution is difficult to explicitly state, it can be shown that the average velocity will tend toward the group velocity of a longitudinal wave. For example, a cold electron will accelerate to a mean velocity of 20% of the wave phase velocity when the wave's amplitude is 50% of the wave breaking

maximum and will be trapped by the wave soon after that if the wave continues to grow. (This effect can be seen in Fig. 3.)

B. Raman Scattering and Wave Mixing

Stimulated Raman Scattering (SRS) is discussed in some detail in reference 10 where growth rates and thresholds are included. The basic physics of SRS will be reviewed here along with an extension to the wave mixing concept.

The SRS instability is a parametric instability, occurring for $n_e \leq n_{crit}/4$, involving three waves: an incident electromagnetic wave with frequency and wave vector (ω_0, k_0) that drives two unstable waves, a scattered electromagnetic wave (ω_1, k_1) and an electron plasma wave (ω_2, k_2) . Where n_{crit} (sometimes n_c) is the critical density above which electromagnetic radiation will not propagate and occurs when the plasma frequency equals the frequency of the electromagnetic wave ($n_{crit} \text{ (cm}^{-3}\text{)} = 1.1 \times 10^{21} / \lambda_0^2 \text{ (}\mu\text{m)}^2$). Frequency and wave vectors must match to produce the unstable conditions, so $\omega_0 = \omega_1 + \omega_2$, and $k_0 = k_1 + k_2$ with the dispersion relations for the electron plasma wave given in Eq.(2) and for the two electromagnetic waves given by

$$\omega^2 = \omega_p^2 + c^2 k^2. \quad (10)$$

The scattered electromagnetic wave can propagate in any direction but always results in a scattered electron plasma wave in the forward hemisphere.

Though an analytical solution cannot easily be written the temperature and density of the plasma uniquely determined the characteristics of both of the scattered waves as a function of scattering direction. As previously

mentioned Raman backscattering is much more likely for most experimental conditions and since the wave mixing concept is usually parametrically the same as Raman forward scattering (sometimes backscattering) only these two scattering directions will be considered here. Thus a specification of the incident radiation and the plasma density and temperature determines ω and k of the electron plasma wave for both forward and backscatter. This EPW is, of course, responsible for the acceleration of the electrons as discussed in the previous sections, and its phase velocity is

$$v_{\phi} = \frac{\omega}{k} = v_{th} \left(\frac{3\omega^2}{\omega^2 - \omega_p^2} \right)^{1/2}. \quad (11)$$

where ω and k are for the EPW. We can determine, therefore, for either forward or backscattering, the phase velocity of the resultant EPW as a function of the plasma temperature and density. This will always give the phase velocity of the EPW but it will need to be interpreted differently when the wave continues to be driven than for a free running wave. For the driven case, a "new" wave will be generated which satisfies the matching conditions at each location so that both ω and k will, in general, vary. For the free running case where a wave is generated in one location and allowed to propagate ω will remain constant and $k(\omega_p)$ will change to satisfy the dispersion relation. Both of these effects will be plotted for a density variation in the next section.

The wave mixing concept involves the illumination of a plasma by two electromagnetic waves. The frequencies of these waves are chosen such that their difference is the frequency of the electron plasma wave whose k is the difference between those of the electromagnetic waves. This is simply the

Raman forward scattering condition if the two electromagnetic waves are parallel or backscattering if the two electromagnetic waves are antiparallel. The primary benefit here is that thresholds for the instability do not need to be exceeded, instead the EPW is driven directly with a linear rather than exponential temporal growth. The major difference is that the EPW frequency, and thus a relationship between T_e and n_e , is uniquely specified. This is also true for SRS with a specified scattered ω but the scattered ω will adjust itself to the plasma conditions, allowing scattering from any density below approximately quarter critical.

C. Electron Plasma Wave Acceleration

An electron plasma wave created by any means propagates through a plasma with phase velocity $v_\phi = \omega/k$ and group velocity $v_g = d\omega/dk$. As the waves propagates ω will remain constant while k varies to match the dispersion relation (Eq. 2). Thus if the EPW propagates into a region of different density or temperatures both the phase and group velocity will, in general, change. Since it is at the phase velocity that trapped electrons will travel we are primarily interested in it though it is at the group velocity that energy is transported. Thus the group velocity is important in considering the range of EPW's or if the particle is to stay with a limited wave packet for an extended time.

Fig. 1 shows the dependence of the phase velocity of an EPW which was created by Raman backscatter in a plasma with $n_e = 5 \times 10^{17} \text{ cm}^{-3}$ and $T_e = 70 \text{ eV}$ (similar to our experimental condition) as it propagates into regions of different but uniform density. Here the electron plasma wave was created with a phase velocity of $.13c$ as determined by the matching conditions. This is indicated by the star in the figure. The electron plasma wave is then assumed to propagate into regions of different density but with a fixed

Fig. 1. For Raman scattering at $n_e = 5 \times 10^{17} \text{ cm}^{-3}$ and $T_e = 70 \text{ eV}$ the phase velocity of the electron plasma wave is indicated by the star. The curve indicates how the phase velocity of this wave will change as it propagates into regions of different density. (Except at $5 \times 10^{17} \text{ cm}^{-3}$, these are not the velocities which will result for Raman scattering at the given densities).

angular frequency. It can be seen in the figure that for an increasing density the phase velocity will increase while it will decrease for a decreasing density. For an increasing density, the effect is quite pronounced and the velocity will be infinite when the plasma frequency (equ. 3) has increased to the wave frequency. Of course the wave is evanescent here. For a wave launched at $n_e = 5 \times 10^{17} \text{ cm}^{-3}$ this will happen when $n_e = 5.12 \times 10^{17} \text{ cm}^{-3}$, a change of only 2.4% for a 70 eV temperature.

For a 1 keV temperature the density change needed is about 40% to achieve this result. This can be seen in Fig. 2 where a series of curves are plotted for both 70 eV and 1 keV plasmas. In this figure the dashed curves indicate the phase velocity of the EPW, at the point where it is created, versus density for Raman forward and backscatter. Also plotted are a series of curves similar to Fig. 1 which indicate how the velocity of this wave will change with changing density, but fixed ω . Thus, it can be seen that a relatively small change in density can result in a tremendous change in the phase velocity of the wave, especially at 70eV or for forward scattering.

An important consideration at this point is under what conditions a trapped particle will remain trapped. Before we address that point we need to consider the amplitude of the trapping electron plasma wave. The wave amplitude can vary from zero to a maximum which can be found in two ways. The first assumes that the electron density variation is so large that all of the electrons have been removed from the rarified regions of the plasma wave, causing wave breaking. The second assumes a cold plasma and that the wave potential will saturate when the wave could accelerate a cold electron to the phase velocity during a single cycle. Both of these methods yield the same peak-to-peak amplitude

$$E_{\max} = \frac{\omega_p^2 m_e}{ek}, \text{ or } \phi_{\max} = \frac{\omega_p^2 m_e}{k^2 e} \quad (12)$$

where $-e$ is the charge of an electron. Depending upon the details of the wave production this has been calculated as the maximum potential attainable.¹⁰

Fig. 2. Electron plasma wave phase velocity vs density for a 70 eV (a) and 1 keV (b) electron temperature. The Raman forward (upper branch) and backscattering (lower branch) electron plasma wave phase velocity at density of creation is indicated by the dotted curve. The solid curves indicate how the velocity will change as the wave propagates into regions of different density with fixed ω .

The question of how long a trapped particle will remain trapped is equivalent to asking if it could be trapped at the velocity which results a period later. This gives from Eq. (6):

$$\Delta v_{\phi} < v_t = 2(v_{osc} v_{\phi})^{1/2}$$

$$\text{or } \frac{\Delta v_{\phi}}{v_{\phi}} < 2 \left(\frac{v_{osc}}{v_{\phi}} \right)^{1/2}$$

Using $v_{\phi} = \omega/k$ we obtain

$$\frac{\Delta k}{k} < 2 \left(\frac{v_{osc}}{v_{\phi}} \right)^{1/2}. \quad (13)$$

This amounts to a constraint on the density gradient up which the electron will remain trapped. This effect, including a relativistic correction has been included in the single particle calculations discussed in the next section.

III. WAVE PARTICLE MODELING

The trajectories of single electrons were studied in the combined fields of three waves: The incident laser radiation, the Raman forward or backscattered radiation, and the resultant electron plasma wave (EPW).

The model includes both Landau and collisional damping and conserves the energy of the EPW as it propagates. The energy conservation results in an increase in the electrical potential if a positive density gradient is encountered without damping. The wave potential at $x = 0$ grows in time to a

value limited to $1/3$ the wave breaking maximum Eq. (12). The wave propagates in space experiencing both damping and growth (if a density gradient is encountered). Its amplitude is, except where noted, limited to $1/3$ the wave breaking maximum at all points in space. Representative computer output will be given for constant density, positive density gradient and periodic density cases.

Constant Density. Fig. 3 shows the time dependence of the velocity of an electron in a uniform plasma with a zero initial velocity in the field of an EPW which is growing in time to a saturation value, but damped in space.

Fig. 3. Plot of electron velocity vs time. The EPW driving the electron oscillations has a constant phase velocity (also plotted) of 2.02×10^{10} cm/s (no density gradient $n_e = 2.35 \times 10^{18}$ cm⁻³).

Notice that the electron oscillatory velocity is increasing as the wave grows, that it suddenly "jumps" to the phase velocity of the EPW; then the oscillatory or bounce velocity decreases as the electron travels into a region where the wave is damped.

Positive Density Gradient. Fig. 4 shows the velocity of an electron and of the EPW at the location of the electron as a function of time. For this case, the wave growth and damping are the same as in the previous case. A density gradient has been included here which results in an increase in the phase velocity with distance traveled. Notice that the electron is

Fig. 4. Plot of electron velocity when a positive density gradient exists. The phase velocity of the wave (at position of electron) is also plotted showing an increase beyond the speed of light.

accelerated though it is never trapped. The apparent oscillation in the EPW velocity arises because it is plotted at the position of the electron.

Figs. 5 and 6 show results of situations with slightly different damping and density gradients. Notice that in Fig. 5 the electron is "kicked over" the EPW phase velocity. The EPW phase velocity then increases very rapidly at the location of the electron, since the electron is now moving so fast. This results in the potential of the wave being insufficient to trap the electron as the velocities cross. Fig. 6 is for conditions quite similar to Fig. 5 except that rather than being "kicked" over the EPW velocity the electron is trapped in an EPW trough. Here, as the wave accelerates more quickly, the potential of the wave is unable to

Fig. 5. Plot of electron velocity as in Fig. 4. ($T_e = 100$ eV, $n_e(\text{cm}^{-3}) = 1.2 \times 10^{18} + 3.0 \times 10^{17} z(\text{cm})$).

Fig. 6. Plot of electron velocity as in Fig. 5. ($T_e = 100$ eV, $n_e(\text{cm}^{-3}) = 3.9 \times 10^{17} + 5.1 \times 10^{17} z(\text{cm})$).

continue accelerating the electron along with it. Notice that in both of these cases the electron detrapped well before attaining the speed of light.

In conventional electron acceleration techniques, the attainment of $v_e = .99c$ ($E=3.6$ MeV) is a relatively easy task. After that we can think of continuing to accelerate or gain energy while traveling at the speed of light. This process is more difficult in general, and particularly here, because without a very carefully chosen density profile the EPW will continue to accelerate past c . Our calculations do show, however, that an electron can be accelerated to quite relativistic values by an EPW traveling up a density gradient. Fig. 7 shows an electron attaining an energy of over 11 MeV. In Fig. 7(a) the velocity is plotted as in previous figures where

Fig. 7. (a) Electron velocity and EPW phase velocity and (b) total electron energy for a carefully picked asymptotically approached final density. ($n_{e0} = 1.97 \times 10^{18} \text{ cm}^{-3}$, $n_{\text{emax}} = 2.0 \times 10^{18} \text{ cm}^{-3}$).

it can be seen to reach $\sim c$ at about 2.3×10^{-12} seconds. Figure 7(b) shows the electron energy versus time where it can be seen to continue accelerating (gaining energy) until 6.8×10^{-12} seconds at which time the calculations was stopped and the electron had an energy of over 21 MeV. Here accelerating potentials as high as about 20 GeV/m are predicted during the process. Since the damping of the EPW depends upon both density and t_e at a determination of a maximum electron energy must include both factors.

Electron plasma waves created by forward Raman scattering in a plasma of uniform density travel just below the speed of light as can be seen in Fig. 2. This precludes using this mechanism in a uniform plasma to accelerate highly relativistic electrons, that is, arbitrarily close to the speed of light. To overcome this it has been proposed to add a magnetic field perpendicular to the direction of propagation of the EPW.⁴ Our results for this effect, termed the "surfatron," will be discussed later.

Periodic Density Profile. Electron acceleration has been studied by computing the electron trajectory in the electric field of an electron plasma wave traveling through a plasma with a periodic density profile. It is theoretically possible to create a series of density bumps such that the beat frequency of two electromagnetic waves corresponds to the density minimum and the maximum corresponds to a density for which the phase velocity of the plasma wave reaches the speed of light. The distance between bumps should be large enough that the waves are damped before the density starts to decrease so that the electrons will not be decelerated. For our plasma conditions this corresponds to a distance of about 1 mm. In this configuration electrons will go from one bump to another without energy loss and become accelerated again for each bump if the electrons reach the

density maxima in proper phase with the waves. Using the previously described computer code, we studied two different types of bumps to analyze this method of acceleration. The first is a sinusoidal oscillation of density with the wave excited at the density minima. Fig. 8 shows the electron energy as a function of time for such a case. In these calculations the wave amplitude was limited by specifying a maximum charge separation of 30%. To compare it with the surfatron⁴, where 100% modulation is used in the calculations, these values should nominally be multiplied by 3. This method can be successful for acceleration to large energies where the electrons travel with the speed of light when the accuracy between bumps is better than 1/4 of the EPW wavelengths. For a CO₂ laser and 1/10 of

Fig. 8. Electron acceleration for Raman backscattering at density minima of a sinusoidal density profile ($n_e = 9.43 \pm 0.1 \times 10^{17} \text{ cm}^{-3}$, $\lambda = 0.11 \text{ cm}$).

critical density this requires an accuracy of about $1 \mu\text{m}$. It is not known how to generate plasma density modulation with such accuracy. Several runs similar to that shown in Fig. 8 allow us to determine an optimum density modulation of about 1% for these conditions (density $1/10$ of critical and temperature $T_e = 300 \text{ eV}$).

More complicated density profiles were also considered. We assumed a density profile which has been previously described but is now periodic. It involves a linear density ramp until the phase velocity of the plasma wave reaches the speed of light, then the density gradient is decreased maintaining the phase velocity at the speed of light. After the plasma wave is damped the density is suddenly lowered to the initial value. The wave is regenerated and the density starts to increase as before. Fig. 9 shows the electron energy as it traverses 43 such density bumps where acceleration of $7.3 \times 10^9 \text{ eV/m}$ was achieved for 100% charge separation. The phase of the wave at some bumps was artificially adjusted by moving the region of rapid density increase so that the electron would coincide with the proper point in the wave. Thus some of the density bumps have a slightly different shape than the rest. This last acceleration method is extremely difficult experimentally unless a phase self-adjusting mechanism is discovered.

Similar calculations have been done for wave mixing conditions analogous to Raman forward scattering. Because the EPW originates at very nearly c , this case requires a density modulation of only 10^{-4} to increase the EPW velocity to c (Fig. 2). Fig. 10 shows a forward scattering case, with 2 density bumps where acceleration of $4.4 \times 10^7 \text{ eV/m}$ was achieved. This has not been carefully optimized, since optimization is much more difficult in this case because plasma conditions have to be specified very precisely. This will make it virtually impossible to achieve experimentally.

Fig. 9. Electron acceleration for Raman backscattering at density minima of an asymptotic periodic density profile as in Fig. 7. ($n_e = 9.43 \pm 0.1 \times 10^{17} \text{ cm}^{-3}$, $\lambda = 0.12 \text{ cm}$).

Surfatron acceleration has been modeled for several cases by including magnetic fields perpendicular to the plasma wave k -vectors. Fig. 11(a) shows the component of the electron velocity in the EPW direction as it is trapped, then oscillates about the EPW velocity. Fig. 11(b) shows the energy of this electron as it is accelerated at an angle to the EPW direction of propagation (acceleration of $8.5 \times 10^8 \text{ eV/m}$ is achieved for 30% charge separation). This run is without wave damping and is for constant plasma density. The wave amplitude decreases with time due to numerical damping only. Comparison of several runs show that the magnitude of the magnetic field is critical in this process and that lower or higher than

Fig. 10. Electron acceleration for forward Raman scattering and an asymptotic periodic density modulation ($n_e = 9.530 \pm 0.001 \times 10^{17} \text{ cm}^{-3}$, $\lambda = 0.10 \text{ cm}$).

optimal field will "untrap" electrons from the plasma wave with the electron losing energy. We did not investigate what determined the optimum value of the magnetic field.

Adding a density modulation with the wave excited only at the density minima is very destructive for surfatron acceleration as can be seen in Fig. 12. In this figure a small density oscillation (2×10^{-4}) causes the acceleration to cease after a short distance. This is because the electron is lost from the wave in jumping from one bump to another. This may create problems for wave mixing surfatron acceleration if the bandwidth of the

Fig. 11. (a) Electron velocity component parallel to the EPW velocity and (b) electron energy for forward Raman scattering and a perpendicular magnetic field. The wave is excited without damping uniformly in space ($B=1$ Tesla $n_e = 9.29 \times 10^{17} \text{ cm}^{-3}$).

Fig. 12. Electron energy for conditions of Fig. 11 but with an added sinusoidal density modulation and the EPW excited only at the density minima. ($n_e = 9.43 \pm 0.1 \times 10^{17} \text{ cm}^{-3}$, $\lambda = 0.11 \text{ cm}$).

laser is smaller than the corresponding plasma frequency modulation so that the matching conditions are only satisfied periodically. For waves excited by Raman scattering instead of wave mixing this should not be a problem since electron plasma waves will be excited over a large density range. The problem of interaction of these plasma waves should, however, be addressed in the future.

IV. CONCLUSION

Several mechanisms can be responsible for the acceleration of cold electrons toward the phase velocity of an electron plasma wave. When the electron is near enough the phase velocity it can be trapped by the wave and travel with an average velocity equal to the phase velocity but with an additional oscillatory component. As the wave damps or accelerates too rapidly, the electron will be released with a velocity determined by both the wave's phase velocity and the electron's oscillatory velocity. We believe that the Maxwellian distributions experimentally observed are a result of a random combination of these parameters for one or more wave packets.

Acceleration of electrons to arbitrarily high energies has been predicted for two mechanisms. For a wave excited at the position of acceleration of a particle with a perpendicular magnetic field the "surfatron"⁴ scheme shows promise. Similarly, unlimited acceleration is predicted for electron plasma waves propagating in a controlled density gradient. The density gradient scheme has the advantage of not needing the perpendicular magnetic field and, in fact, allowing a parallel magnetic field for plasma confinement. It does, however, place very stringent constraints on the plasma density control. Accurate density control is also important to other plasma wave accelerator schemes including the "surfatron" method. This constraint is higher for low temperatures so that a high plasma temperature may be required for effective acceleration.

Though electron acceleration by plasma waves shows distinct advantages over conventional accelerators, there are many experimental difficulties which must be overcome before its practical application.

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