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Relativistic Focusing and Beat Wave Phase Velocity Control in the Plasma Beat Wave Accelerator

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Relativistic focusing allows two colinear short pulse radiation beams, provided they are of sufficiently high power, to propagate through a plasma without diffracting. By further accounting for finite radial beam geometry, it is possible for the phase velocity of the radiation beat (ponderomotive) wave to equal the speed of light. This removes one of the limiting factors, phase detuning between the accelerated electrons and the beat wave, in determining the maximum energy gain in the plasma beat wave accelerator.

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RELATIVISTIC FOCUSING AND BEAT WAVE PHASE VELOCITY CONTROL IN THE PLASMA BEAT WAVE ACCELERATOR

Introduction

Recently there has been much interest in plasma based accelerator schemes, such as the plasma beat wave accelerator (PBWA),[1-3] for producing ultra-high energy electrons. This has led to a renewed interest in the study of the propagation of intense radiation beams through a plasma.[4-13] In the PBWA two colinear radiation beams of frequencies ω_1, ω_2 are incident on a uniform plasma. By appropriately choosing the difference in the laser frequencies to be equal to the electron plasma frequency ω_p, $\Delta\omega = \omega_1 - \omega_2 = \omega_p$, where $\omega_p^2/\omega_1^2 << 1$, it is possible for the radiation beat wave to resonantly drive large amplitude electron plasma waves. In the ideal wave breaking limit,[14] the maximum accelerating electric field E_m is given by $E_m = (m_e c^2/e)\omega_p/c \simeq .97\sqrt{n_p}$ eV/cm where n_p is the plasma density in cm^{-3}. For example, $n_p = 1.6 \times 10^{16}$ cm^{-3} gives $E_m \simeq 120$ MeV/cm which implies that an electron could be accelerated to 1.2 TeV in 100 meters.

To realize such an acceleration scheme it is necessary that *i)* the radiation beams propagate at high intensity over distances large compared to the Rayleigh length $z_R = \omega r_s^2/2c$, where r_s is the radiation spot size, and that *ii) phase resonance* between the accelerating electrons and the plasma wave be maintained over an equally large distance. In vacuum, radiation diffracts over distances on the order of z_R, which can be relatively short. Hence, in order to maintain high intensity beams it is necessary to rely on focusing enhancement from the plasma. In the PBWA the phase velocity of the plasma wave is equal to the phase velocity of the radiation beat wave which, in the 1-D limit, is given by $v_p/c = \Delta\omega/\Delta k \simeq 1 - \omega_p^2/2\omega_1^2$, where $\Delta k = k_1 - k_2$ is the difference in the wave numbers of the two beams. Since the velocity of an ultra-relativistic electron is approximately the speed of light, the electrons out run the plasma wave and become "detuned" in a length[15] $L_d \simeq \lambda_p \omega_1^2/\omega_p^2$, where $\lambda_p = 2\pi c/\omega_p$. For $\omega_1/\omega_p = 25$ and $n_p = 1.6 \times 10^{16}$ cm^{-3}, this gives $L_d \simeq 16$ cm and a maximum electron energy gain of $\Delta\mathcal{E} \simeq E_m L_d \simeq 2$ GeV. In order to increase the energy gain beyond this detuning limit, it is necessary to increase the phase velocity of the plasma beat wave.

This paper addresses the two points mentioned above concerning the realization of the PBWA. As is shown below, matched beam solutions are possible in which the two radiation beams propagate with constant spot sizes provided the radiation is of sufficiently high power. This allows the radiation beams to propagate over distances larger than the Rayleigh length while maintaining their high intensities. For example, two radiation beams with equal spot sizes are matched provided the power in each beam is $P = P_c \ 3$.

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where $P_c \simeq 17 \times 10^9 \omega^2/\omega_p^2$ W is the power threshold for relativistic focusing of a single radiation beam in a plasma.[4-8] In addition, by including finite radial beam profiles along with relativistic focusing, the phase velocity of the beat wave can be tuned to the speed of light. This is accomplished by appropriately choosing the initial spot sizes and powers of the radiation beams. Hence, phase resonance between the electron and beat wave can be maintained beyond the 1-D detuning length L_d and, consequently, substantially higher electron energies can be achieved. Figure 1 shows schematically the propagation of two matched radiation beams through a plasma with the resulting beat wave phase velocity equal to the speed of light.

Focusing of radiation beams in a plasma occurs through the combined effects of relativistic, ponderomotive and thermal self-focusing.[4-13] Typically these processes occur on widely separate time scales. Relativistic focusing[4-8] occurs on the shortest time scale, $\tau_R \sim 1/\omega$, which is the time scale at which the electrons respond to the radiation field. Ponderomotive focusing[9-11] depends on the expulsion of ions from the radiation channel and thus occurs on a time scale given roughly by $\tau_P \sim r_s/C_s$, where C_s is the ion acoustic speed. Thermal focusing[12,13] relies on heating of the plasma by the radiation beam and typically occurs on an even longer scale. This paper is concerned with relativistic focusing, and hence the analysis is applicable to lasers with pulse lengths τ_L in the range $\tau_R < \tau_L < \tau_P$, which is the region of interest for the PBWA. Physically, relativistic focusing arises solely from the relativistic electron quiver velocity, $v_q = ca_\perp/\gamma_\perp$, in the combined radiation field. Here $a_\perp = eA_\perp/mc^2$ is the normalized radiation vector potential and $\gamma_\perp = \sqrt{1 + a_\perp^2}$ is the relativistic gamma factor for an electron in a helically polarized radiation field. The focusing mechanism for a single beam is that a radiation profile peaked on axis leads to an index of refraction profile, $n \simeq 1 - (\omega_p/\omega)^2/2\gamma_\perp$, which has a minimum on axis. The radiation beam, therefore, focuses along the axis.[7] When the radiation power is greater than the critical power P_c for relativistic self-focusing, it is possible for the envelope of a single radiation beam to propagate at a constant spot size.[7] For two colinear beams, however, the situation is more complicated due to the coupling of one beam to the other through the relativistic gamma factor. The analysis presented below indicates that matched beam propagation for two beams is only possible for a finite range of the parameter R, such that $1/(\sqrt{8} - 1) < R < \sqrt{8} - 1$, where $R = (r_{s1}/r_{s2})^2$ is the square of the ratio of the spot sizes of the two beams. The radiation power required to obtain matched beam propagation for two beams is near that for a single beam, P_c.

Control of the beat wave phase velocity is most easily understood by the following heuristic argument. The finite radial extent of the radiation beams gives rise to a small effective perpendicular wave number $k_\perp$. Here $k_\perp$ is a function not only of the spot size but also of the power due to the relativistic focusing effects. The existence of $k_\perp$ gives rise to an effective parallel wave number given by $k_\parallel \simeq (1 - \omega_p^2/2\omega^2 - c^2k_\perp^2/2\omega^2)\omega/c$. Hence, the parallel phase velocity of the beat wave is now given by $v_p/c \simeq 1 - \omega_p^2/2\omega^2 + (k_{\perp 1}^2 - k_{\perp 2}^2)c^2/2\omega\omega_p$. By appropriately choosing the initial spot sizes and powers of the two radiation beams, it is possible to have the last term in the expression for v_p/c cancel the second term thus providing $v_p = c$.

Analysis of Radiation Focusing and Beat Wave Phase Velocity Control

The analysis starts with the wave equation for the vector potential of the combined radiation field, $(\nabla^2 - c^{-2}\partial^2/\partial t^2)A_\perp = -(4\pi/c)J_\perp$, where $J_\perp$ is the transverse current density. In order to study the effects of relativistic focusing alone, only the current resulting from the electron quiver motion is needed, $J_\perp = -en_pv_q$. The wave equation is then given by

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) a_\perp = \frac{\omega_p^2}{c^2} a_\perp \left(1 + |a_1|^2 + |a_2|^2 + 2|a_1||a_2|\cos\Delta\Phi\right)^{-1/2}, \qquad (1)$$

where $a_\perp = a_1 + a_2$. Throughout the following, a subscript 1 refers to the radiation beam of frequency ω_1, and a subscript 2 refers to the radiation beam of frequency ω_2. The factor within the square root is the relativistic gamma factor $\gamma_\perp$, assuming helically polarized radiation. Here, $\Delta\Phi = \Phi_1 - \Phi_2$ is the phase of the beat wave and $\Phi_{1,2} = k_{1,2}z - \omega_{1,2}t + \phi_{1,2}$, where $\phi_{1,2}$ is the slowly evolving phase of the radiation field.

In order to examine the qualitative diffractive properties of the radiation beams, it is helpful to consider the index of refraction $n_{1,2}$ of each beam. The approximate index of refraction associated with each beam is obtained in the following manner. First, the 1-D limit of the left hand side of Eq. (1) is taken, assuming $a \sim \exp(i\Phi)$. Next, Eq. (1) is divided by the phase factor $\exp(i\Phi)$ of either beam 1 or 2 and then averaged over a period of the beat phase $\Delta\Phi$. In the mildly relativistic limit $|a_{1,2}|^2 < 1$, the index of refraction for each beam is given by

$$n_1 = k_1c/\omega_1 = 1 - (\omega_p^2/2\omega_1^2)(1 - |a_1|^2/2 - |a_2|^2), \qquad (2a)$$

$$n_2 = k_2c/\omega_2 = 1 - (\omega_p^2/2\omega_2^2)(1 - |a_1|^2 - |a_2|^2/2). \qquad (2b)$$

In the above expressions, the first term (the unity) represents vacuum diffraction while the second term is the contribution from the ambient plasma. The remaining terms represent focusing from the radiation fields. More specifically, a term proportional to $(|a_1|^2 + |a_2|^2)/2$

results from the individual contributions of beam 1 and 2 to the relativistic factor $\gamma_\perp$, while the remaining term proportional to $|a_{1,2}|^2/2$ results from the contribution of the beat wave to $\gamma_\perp$. Radiation focusing occurs when $\partial n/\partial r < 0$. Hence, the contribution from the radiation terms to $n_{1,2}$ provide focusing for radiation profiles peaked on axis. For sufficiently high power, these focusing terms dominate the vacuum diffraction and provide overall focusing of the radiation beams.

Envelope equations describing the evolution of the spot size $r_s(z)$ of each beam are derived by applying the "source–dependent expansion" (SDE)[16,17] to Eq. (1). This is accomplished by expanding the normalized vector potential $a_{1,2}$ for each beam into a series of Gaussian–Laguerre polynomials and using orthogonality properties to determine their coefficients. The SDE differs from the typical vacuum modal expansion in that the parameters characterizing the Gaussian–Laguerre polynomials, such as the width of the Gaussian, are functions of z which depend on the "source", i.e. the right hand side of Eq. (1). Assuming that each beam is adequately described by the lowest order Gaussian mode $a = |a_{00}|\exp[i\beta - (1 - i\alpha)r^2/r_s^2]$, then the parameters $|a_{00}|$, β, α and r_s are given by $|a_{00}(z)| = a_0 r_{s0}/r_s(z)$, $\alpha(z) = (\omega/4c)dr_s^2/dz$ along with the following equations:

$$\frac{d^2}{dz^2} r_{s1} = \frac{4c^2}{\omega_1^2 r_{s1}^3}\left[1 - W_1\left(1 + \frac{8W_2R^2}{W_1(1+R)^2}\right)\right], \tag{3a}$$

$$\frac{d^2}{dz^2} r_{s2} = \frac{4c^2}{\omega_2^2 r_{s2}^3}\left[1 - W_2\left(1 + \frac{8W_1}{W_2(1+R)^2}\right)\right], \tag{3b}$$

$$\frac{d}{dz}\beta_1 = -\frac{2c}{\omega_1 r_{s1}^2}\left[1 + \frac{\omega_p^2 r_{s1}^2}{4c^2} - W_1\left(\frac{3}{2} + \frac{4W_2R(1+2R)}{W_1(1+R)^2}\right)\right], \tag{4a}$$

$$\frac{d}{dz}\beta_2 = -\frac{2c}{\omega_2 r_{s2}^2}\left[1 + \frac{\omega_p^2 r_{s2}^2}{4c^2} - W_2\left(\frac{3}{2} + \frac{4W_1(2+R)}{W_2(1+R)^2}\right)\right], \tag{4b}$$

where the mildly relativistic limit was taken, $|a_{1,2}|^2 < 1$. Physically, $W = (\omega_p a_0 r_{s0}/4c)^2 = P/P_c$ where P is the power in one of the beams and P_c is the critical power necessary for relativistic focusing of a single beam.[7] Here a_0 and r_{s0} are the initial amplitude of the vector potential on axis and the initial spot size of each beam. The parameter α is related to the curvature of the radiation wavefront and the parameter β is important in that it represents a correction to the parallel wave number on axis $k_\parallel = \omega/c + d\beta/dz$. This relation is used below to determine the beat wave phase velocity on axis.

Equations (3a) and (3b) describe the envelope evolution for each beam as it propagates through the plasma. Setting the right–hand sides of Eqs. (3a) and (3b) equal to zero gives matched beam solutions for which the beams propagate without diffracting. Matched beam solutions are obtained for values of R in the range $1/(\sqrt{8}-1) < R < \sqrt{8}-1$ provided the normalized power W of each beam is given by

$$W_1 = [8R^2(1+R)^2 - (1+R)^4][64R^2 - (1+R)^4]^{-1}, \tag{5a}$$

$$W_2 = [8(1+R)^2 - (1+R)^4][64R^2 - (1+R)^4]^{-1}. \tag{5b}$$

This is illustrated in the following limits: For $R = 1$, then $W_1 = W_2 = 1/3$. As $R \to 1/(\sqrt{8}-1)$, then $W_1 \to 0$ and $W_2 \to 1$. As $R \to \sqrt{8}-1$, then $W_1 \to 1$ and $W_2 \to 0$. Hence, it is possible for a beam close to the critical power to confine a second beam which has a smaller spot size and a smaller power.

Matched beam propagation occurs when R, W_1 and W_2 are specified as indicated above. For example, once R is chosen in the range $1/(\sqrt{8}-1) < R < \sqrt{8}-1$, then W_1 and W_2 are given by Eqs. (5a) and (5b). The actual magnitudes of the spot sizes r_{s1} and r_{s2} are undetermined and only their ratio has been specified. Specifying a value for r_{s1} gives a value for the radiation beat wave phase velocity on axis according to the relation $c/v_p = 1 + c\Delta\beta'/\Delta\omega$, where $\Delta\beta' = d\beta_1/dz - d\beta_2/dz$. Alternatively, requiring $v_p = c$ for a given set of matched beam parameters R, W_1 and W_2 specifies r_{s1}. For example, as $R \to \sqrt{8}-1$, requiring $v_p = c$ gives $k_p^2 r_{s1}^2 \simeq 5\omega_1/\Delta\omega$, where $k_p = \omega_p/c$. For $R = 1$, requiring $v_p = c$ gives $k_p^2 r_{s1}^2 \simeq 2$. As $R \to 1/(\sqrt{8}-1)$, it is not possible to have $v_p = c$. For applications in the PBWA, it may be desirable to have $k_p^2 r_{s1}^2 >> 1$. This implies that it may be desirable to choose a matched beam case with $R > 1$. For example, $R = 1.5$ gives $W_1 \simeq 0.7$, $W_2 \simeq 0.1$ and $k_p^2 r_{s1}^2 \simeq 2.6\omega_1/\Delta\omega$.

As a final illustration, the above results are applied to parameters similar to those in the UCLA beat wave excitation experiment,[18] where $\omega_1 \simeq 2.0 \times 10^{14}$ sec^{-1} and $\Delta\omega/\omega_1 \simeq 9.7 \times 10^{-2}$ (which implies $n_p \simeq 10^{17}$ cm^{-3}). A test electron with intial energy given by $\gamma_0 = 50$ is accelerated by plasma waves generated in the following two special cases: *i*) A matched beam case with the beat wave phase velocity tuned to the speed of light, $v_p = c$, where $R = 1.5$, $r_{s1} = 8.3 \times 10^{-3}$ cm, $P_1 = 1.3 \times 10^{12}$ W and $P_2 = 1.6 \times 10^{11}$ W; and *ii*) the same parameters as case *i*) only now the beat wave phase velocity is given by the 1-D limit, $v_p/c \simeq 1 - \omega_p^2/2\omega_1^2$, and the radiation beams are assumed to undergo vacuum Rayleigh diffraction, $r_s = r_{s0}(1 + z^2/z_R^2)^{1/2}$. The results of case *ii*) are shown in Fig. 2 and the results of case *i*) are shown in Fig. 3. Figure 2 indicates that the test electron outruns the plasma wave and begins to be deaccelerated after approximately 0.5 cm with a maximum energy gain of $\Delta\gamma \simeq 210$. In Fig. 3, however, phase resonance between the electron and beat wave is maintained which allows an energy gain of $\Delta\gamma \simeq 6500$ in 8 cm. This energy gain continues in a linear fashion until it becomes limited by some non-ideal effect such as pump depletion.[19]

Discussion

In summary, it has been shown that two colinear, short-pulse, Gaussian radiation beams can propagate through a uniform plasma without diffracting due to relativistic focusing. This occurs for values of R in the range $1/(\sqrt{8}-1) < R < \sqrt{8}-1$, provided W_1 and W_2 are specified according to Eqs. (5a) and (5b). In addition, it is possible to tune the phase velocity of the radiation beat wave to the speed of light for cases where $R \geq 1$. This is accomplished by appropriately choosing r_{s1}. In an actual PBWA, $\Delta\omega = \omega_p$ and the envelope behavior of the radiation beams becomes more complicated due to the presence of large amplitude resonantly driven plasma waves.[20] However, the analysis presented here remains valid for the front of the radiation pulse (the first several plasma wavelengths) where the amplitude of the plasma wave remains small. In the small amplitude limit, the phase velocity of the plasma wave is equal to that of the radiation beat wave.[21] Assuming that the phase velocity of the plasma wave remains fixed to its initial value, then the above analysis indicates that it is possible to tune this phase velocity to the speed of light. This implies that phase detuning between the plasma wave and the electrons can, in principle, be avoided which results in a substantially higher energy gain in the PBWA.

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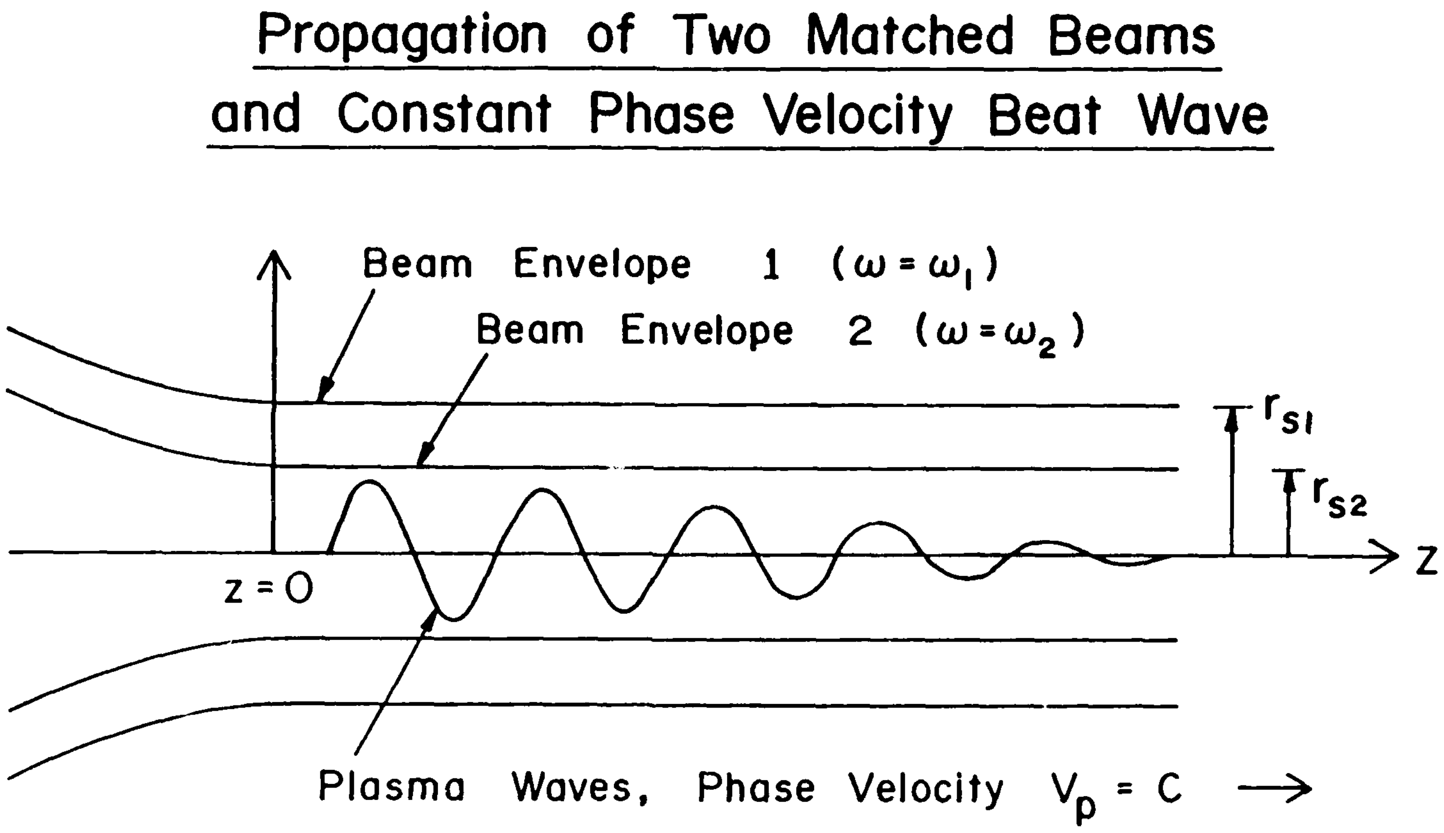

FIG. 1. Schematic of the PBWA for matched propagation of two radiation beams with constant spot sizes where the resulting beat wave phase velocity equals the speed of light.

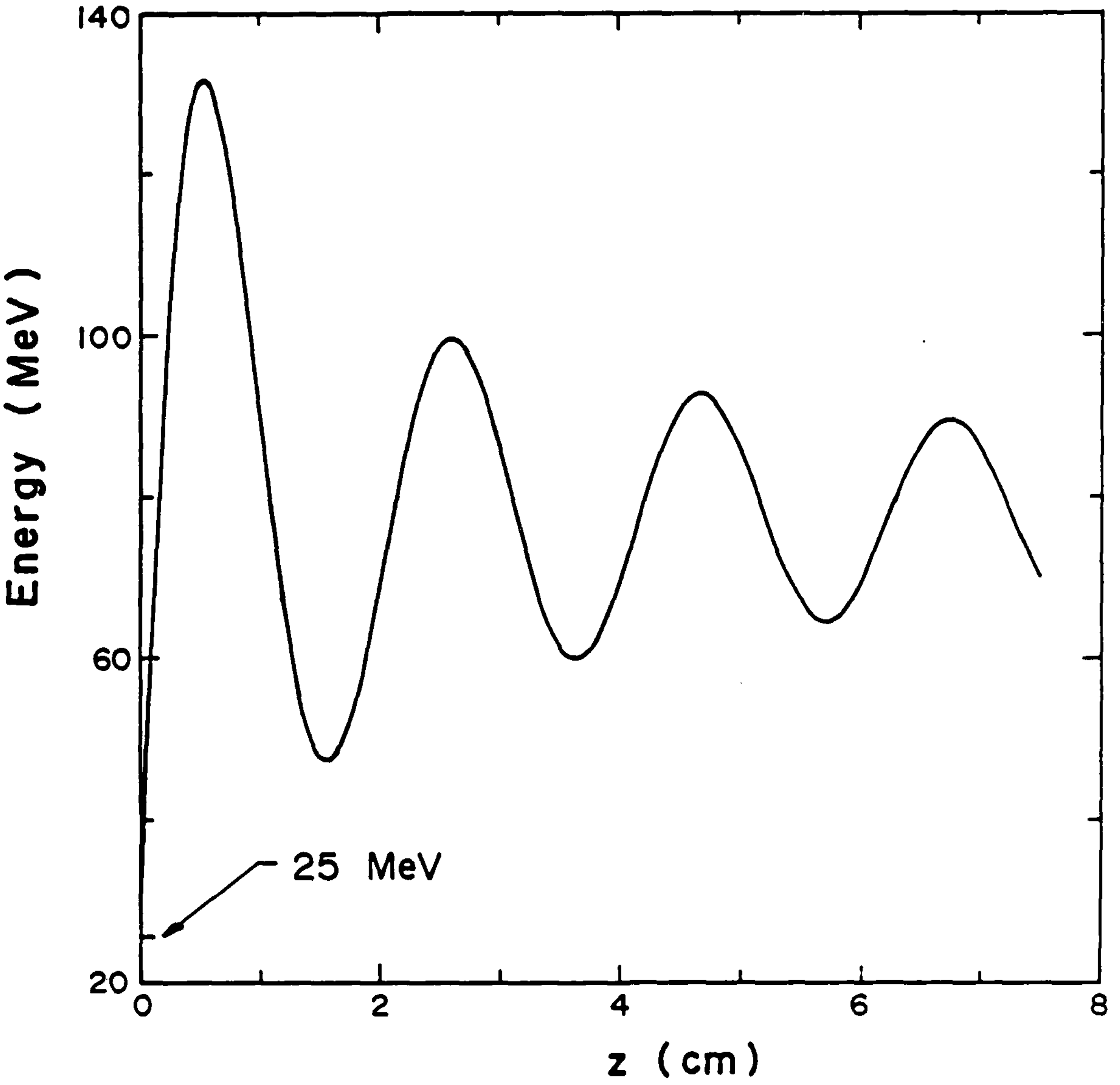

FIG. 2. Test electron acceleration with the same parameters as Fig. 3 except the phase velocity is given by the 1-D limit and the radiation beams undergo vacuum Rayleigh diffraction.

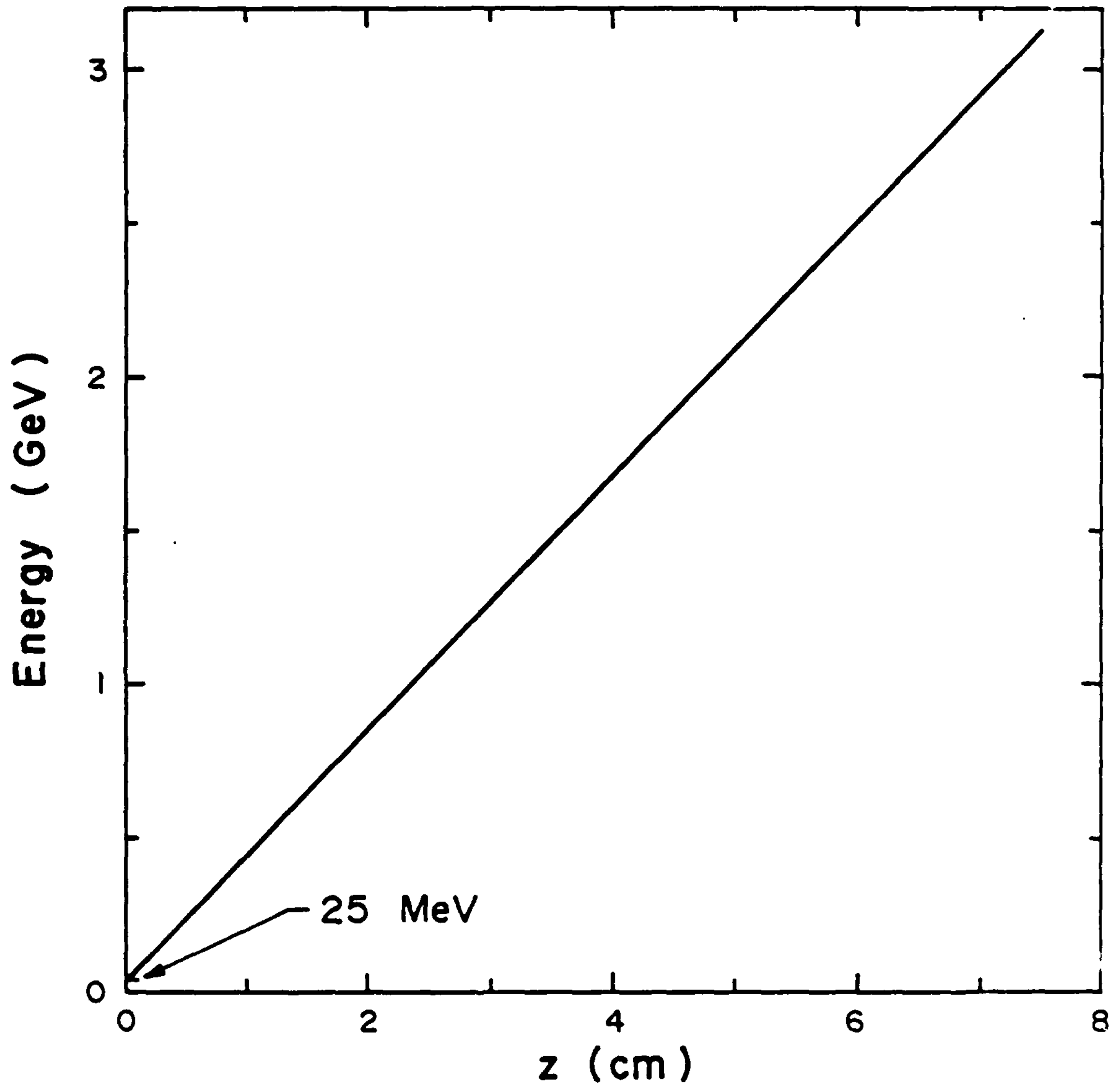

FIG. 3. Test electron acceleration for a matched beam case with $v_p = c$, where $R = 1.5$, $r_{s1} = 8.3 \times 10^{-3}$ cm, $P_1 = 1.3 \times 10^{12}$ W and $P_2 = 1.6 \times 10^{11}$ W.

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