SLAC – PUB – 3934
April 1986
(A)

Progress on Laser Plasma Accelerators*

PISIN CHEN**

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

Abstract

Several laser plasma accelerator schemes are reviewed, with emphasis on the Plasma Beat Wave Accelerator (PBWA). Theory indicates that a very high acceleration gradient, of order 1 GeV/m, can exist in the plasma wave driven by the beating lasers. Experimental results obtained on the PBWA experiment at UCLA confirms this. Parameters related to the PBWA as an accelerator system are derived, among them issues concerning the efficiency and the laser power and energy requirements are detailly discussed.

1. Introduction

The acceleration gradient attainable from the currently existing high energy accelerators is around 20 MeV/m. To extend the present technology to future ultra-high energy accelerators, the sizes are necessarily be enormous. In recent years, various novel ideas on future accelerators have been proposed,[1,2] among them plasma accelerators[3] promise to provide very high gradients.

Plasmas are known to exhibit oscillations where electrons and ions execute periodic motions. For fully ionized plasmas with density n_0 particles per cm^3 for each spices, a density perturbation n_1 due to charge separation during oscillation would provide an instantaneous longitudinal electrostatic field $\vec{E}$, *i.e.* $\nabla \cdot \vec{E} \sim k_p E \sim 4\pi e n_1$, where $k_p = \omega_p/c$ is the plasma wave number. Since the maximal possible density perturbation is $n_1^{\max} \sim n_0$, the maximal acceleration gradient provided by the $\vec{E}$ field is $eE^{\max} \sim 4\pi e^2 n_0/(\omega_p/c) \sim \sqrt{n_0}$ eV/cm. For a laboratory plasma of density $n_0 = 10^{18}$ cm^{-3}, we have $eE^{\max} \sim 100$ GeV/m. This is more than 3 orders of magnitude better than that of the conventional accelerators.

For an effective acceleration of relativistic particles, it is necessary that the plasma wave phase velocity be close to c, the speed of a high energy injected electron beam. To achieve such a plasma oscillation several ideas employing lasers have been suggested. The Plasma Beat Wave Accelerator (PBWA)[4] uses two laser beams beating at the plasma frequency ω_p, while the Plasma Grating Accelerator[5] side-injects a polarized laser beam on a plasma where static ion ripples are prepared by an acoustic wave. Other concepts like the Plasma Fiber Accelerator[6] and the "Surfatron"[7] are variants of the PBWA aiming at improving its deficiency in different ways. There are various other proposals on laser plasma accelerators,[1,2] but we are not covering them here.

In this paper we review primarily the concept of PBWA. Other laser plasma accelerator schemes mentioned above will only be discussed auxiliary to the PBWA. Our approach, which follows closely to Refs. 8 and 9, is to consider the PBWA as a system, and to look for a self-consistent set of parameters such that the system is operative. This serves as a guidance for laboratory test of principle experiments, and for the discussion on various laser requirements.

2. Physical Mechanisms of Plasma Wave Generation

2.1 The Ponderomotive Force in a Plasma

It is well known that a plane electromagnetic wave cannot cause any net drift of a charged particle along its direction of propagation. An originally stationary charged particle experiencing such a EM wave would execute a "figure 8" closed orbit motion. Consider now two beating EM waves. In this situation the amplitudes of the EM fields vary along the direction of propagation. Accordingly the force due to the magnetic field does not balance to that due to the electric field, and the charged particle would drift in the longitudinal direction. This net force is called the ponderomotive force.

A plasma can be driven resonantly by the beating lasers through the ponderomotive force if the frequency and wave number differences between the two lasers match with those of the plasma wave, *i.e.* $\omega_p = \omega_1 - \omega_2$ and $k_p = k_1 - k_2$, where ω_i and k_i are the frequency and wave number of the two lasers, and ω_p the plasma frequency, $\omega_p \equiv [4\pi e^2 n_0/m]^{1/2}$. The force that excites the plasma is most easily calculated from a Hamiltonian which has been averaged over the fast oscillations of the

* Work supported in part by the Department of Energy, contract DE-AC03-76SF00515 and by the National Science Foundation, contract NSF-PHY-84-20958.

** Department of Physics, University of California, Los Angeles, California 90024.

Invited talk presented at the SPIE Laser'86, Québec, Canada, June 2-6, 1986

laser frequency. This leaves only the beating effect of the two laser frequencies. Assuming that the difference in frequency between the two laser lines is much smaller than the laser frequency, the averaged Hamiltonian can be written as

$$\langle H \rangle = \frac{\vec{p}^2}{2m} + \frac{e^2 E_0^2(r)}{4m\omega^2} \left[1 + \cos(k_p z - \omega_p t)\right] \quad , \tag{1}$$

where we have dropped the index on laser frequencies on ω. The last term is the ponderomotive potential due to a beating laser with a finite cross section.

Assume that the radial dependence of the ponderomotive potential is given by

$$E_0^2(r) = 2E_0^2 \begin{cases} K_2(k_p a)\, I_0(k_p r) + \frac{1}{2} - \frac{2}{(k_p a)^2} - \frac{r^2}{2a^2} & r < a \\ I_2(k_p a)\; K_0(k_p r) & r > a \end{cases} \quad . \tag{2}$$

where K_n and I_n are modified Bessel functions. This radial profile is parabolic near the origin but falls off exponentially for $r > a$. It is chosen to yield a simple parabolic dependence in the ponderomotive force expression below and to simplify the discussions on the transverse behaviors of the PBWA in the following sections.

To use the above results we need the divergence of the force due to the Hamiltonian in Eq. (1). This is given by

$$\nabla \cdot \vec{F} = 4\pi e^2 n_1 + e^2 B_0(r) + e^2 B_1(r)\, \cos(k_p z - \omega_p t) \quad , \tag{3}$$

where n_1 is the plasma density perturbation and

$$B_0(r) = \begin{cases} \frac{E_0^2\, k_p^2}{2m\omega^2} \left(K_2(k_p a)\, I_0(k_p r) - \frac{2}{k_p^2 a^2} \right) & r < a \\ 0 & r > a \end{cases} \quad ; \quad B_1(r) = \begin{cases} \frac{E_0^2\, k_p^2}{4m\omega^2} \left(1 - \frac{r^2}{a^2}\right) & r < a \\ \frac{E_0^2\, k_p^2}{2m\omega^2}\, I_2(k_p a)\, K_0(k_p r) & r > a \end{cases} \quad . \tag{4}$$

2.2 The Plasma Response to the Beating Lasers

To find the plasma response to the ponderomotive force and the electric field associated with the plasma wave, we work with the linearized, nonrelativistic fluid equations in a plasma,

$$\frac{\partial n_1}{\partial t} + n_0\, (\nabla \cdot \vec{v}_1) = 0 \quad , \quad \frac{\partial \vec{v}_1}{\partial t} = \frac{e\vec{\mathcal{E}}_1}{m} + \frac{\vec{F}}{m} \quad , \tag{5}$$

and solve for the perturbed plasma density n_1. $\vec{\mathcal{E}}_1$ is the electric field due to n_1 and $\vec{F}$ is the ponderomotive force.

The plasma is supposed to be so underdense that $\omega_p \ll \omega_1 \approx \omega_2 \equiv \omega$. Therefore the phase velocity of the plasma wave is matched to the "phase velocity" of the beat pattern. This is the group velocity of EM waves in a plasma,

$$v_p^{\text{plasma}} = \frac{\omega_p}{k_p} \simeq \frac{d\omega}{dk} = v_g^{\text{laser}} = c \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2} \quad . \tag{6}$$

Solving for Eq. (5) with $\nabla \cdot \vec{\mathcal{E}}_1 = 4\pi e n_1$, we find

$$\frac{\partial^2 n_1}{\partial t^2} + \omega_p^2 n_1 = -\frac{\omega_p^2}{4\pi} \left[B_0(r) + B_1(r)\, \cos(k_p z - \omega_p t)\right] \quad . \tag{7}$$

If the laser pulse begins at $k_p z - \omega_p t = 0$ and the plasma is unperturbed ahead of it, the solution of the above equation is

$$n_1(r,z,t) = -\frac{B_0(r)}{4\pi} \left[1 - \cos(k_p z - \omega_p t)\right] - \frac{B_1(r)}{8\pi}\, (k_p z - \omega_p t)\, \sin(k_p z - \omega_p t) \quad . \tag{8}$$

The expression has two distinct terms. The first term is due to the shock excitation of the plasma by the front of the laser pulse, while the second term is due to the resonant driving of the plasma by the beating lasers. Since we would like to have the second term build up over many cycles, the second term will be much larger than the first term. In addition, in an actual device the laser pulse would turn on more gradually thus reducing the shock excitation. For these reasons we will neglect the first term in Eq. (8) in the following analysis.

In this treatment the plasma perturbation grows linearly in time during which the laser pulse extents (see Fig. 1). Beyond the linear regime the growth saturates due to various effects. One effect is the relativistic frequency detuning[10] where the plasma frequency shifts to $\omega_p/\gamma^{3/2}$ when the electrons in the plasma becomes relativistic. In this case the laser drive is off resonance, and the perturbation saturates at a maximum value n_1^{max},

$$\left(\frac{n_1}{n_1^{max}}\right)_{saturation} = \left[\frac{16}{3}\left(\frac{eE_1^{laser}}{m\omega_1 c}\right)\left(\frac{eE_2^{laser}}{m\omega_2 c}\right)\right]^{1/3} \equiv \left[\frac{16}{3}\,\alpha_1\alpha_2\right]^{1/3} . \tag{9}$$

Another degradation comes from strong couplings between the primary beat wave and the larger k secondary electrostatic modes.[11] It is found experimentally that this effect saturates the beat wave amplitude well below that expected from relativistic detuning. In this paper we consider modest α_i's such that various nonlinear effects can be neglected. For a laser pulse duration τ the maximum perturbation is therefore (from Eq. (8))

$$n_1^{max}(r) = \frac{\omega_p \tau E_0^2 k_p^2}{32\pi m\omega^2}\left(1-\frac{r^2}{a^2}\right) \qquad r < a \ . \tag{10}$$

The longitudinal and transverse electric fields for $r < a$ can be found by solving the Poisson's equation, $\nabla^2\phi_1 = -4\pi e n_1$, and are given by[8]

$$\begin{aligned} \mathcal{E}_z &= -\frac{\omega_p \tau k_p e E_0^2}{4\omega^2 m}\left\{K_2(k_p a)\,I_0(k_p r) + \frac{1}{2}\left(1-\frac{r^2}{a^2}\right) - \frac{2}{(k_p a)^2}\right\}\cos(k_p z - \omega_p t) \ , \\ \mathcal{E}_r &= -\frac{\omega_p \tau k_p e E_0^2}{4\omega^2 m}\left\{K_2(k_p a)\,I_1(k_p r) - \frac{r}{k_p a^2}\right\}\sin(k_p z - \omega_p t) \ . \end{aligned} \tag{11}$$

For reasons which we will discuss later, the transverse size of the driven beam must be somewhat smaller than the transverse size of the laser beams. In addition if $k_p a \gg 1$, then the fields in Eq. (11) takes the following form:

$$\begin{aligned} \mathcal{E}_z &\simeq -\frac{\omega_p \tau k_p e E_0^2}{8\omega^2 m}\left(1-\frac{r^2}{a^2}\right)\cos(k_p z - \omega_p t) \\ \mathcal{E}_r &\simeq \frac{\omega_p \tau k_p e E_0^2}{4\omega^2 m}\,\frac{r}{k_p a^2}\,\sin(k_p z - \omega_p t) \end{aligned} \qquad r \ll a \ . \tag{12}$$

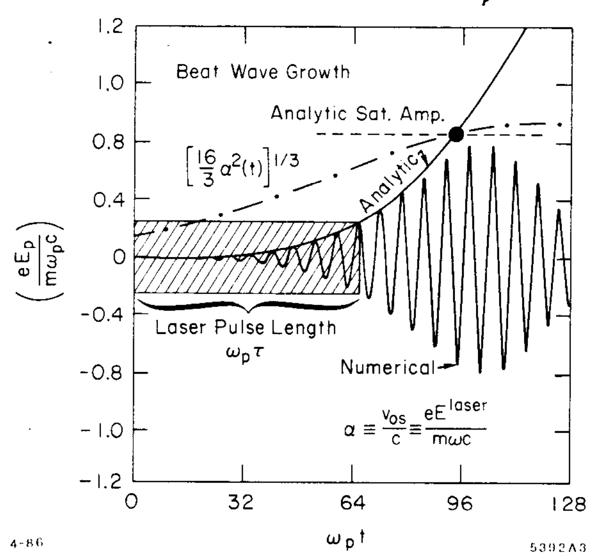

Fig. 1. Analytic and numerical calculations of the plasma beat wave growth in time.

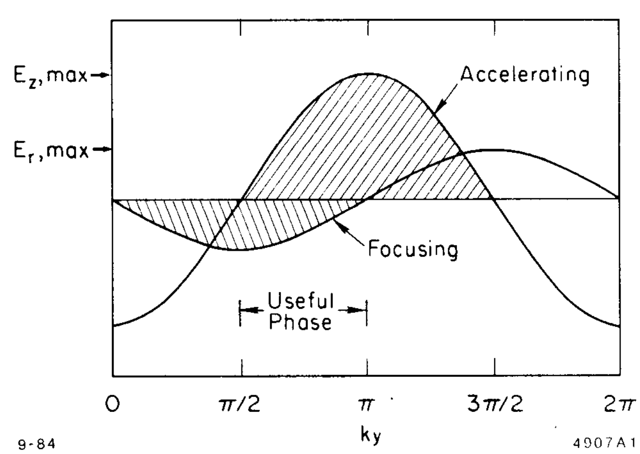

Fig. 2. The longitudinal and transverse components of the plasma wave driven by a beating laser.

We see that, characteristically in the plasma wave there is a longitudinal force $e\mathcal{E}_z$ that either accelerates or decelerates the driven bunch of electrons, and there is a transverse force $e\mathcal{E}_r$ shifted in phase which either focuses or defocuses the driven bunch (see Fig. 2). From Fig. 2 it is clear that we have both acceleration and focusing over 1/4 of the plasma wavelength.

2.3 The Plasma Grating Scheme

As mentioned in the Introduction, there are generically two types of laser plasma accelerators. The PBWA represents the type where the laser beam (or beams) travels collinearly with the accelerated electron bunch. The other type, represented by the Plasma Grating Accelerator,[5] employs side-injected laser which is polarized along the direction of a static density ripple in the plasma (see Fig. 3), $n(z) = n_0 + n_1(z) = n_0 + \delta n \sin k_r z$, where k_r is the wave number of the density ripple. Such a ripple might be produced by an ion acoustic wave or by ionizing a grating. The laser field wiggles the electrons in the ripple by an amount $\delta z = (eE_0/m\omega^2)\cos\omega_0 t$, while the ions are too massive to respond. This produces a longitudinal electric field disturbance given by the Poisson equation:

$$\frac{\partial E_z}{\partial z} = 4\pi e\delta n = 4\pi e\,\frac{\partial n}{\partial z}\,\delta z \simeq \frac{\omega_p^2}{\omega_0^2}\,\frac{\delta n}{n_0}\,E_0 k_r \cos k_r z \cos\omega_0 t \quad . \tag{13}$$

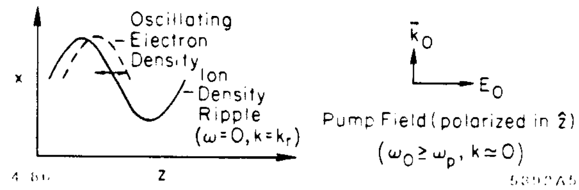

Fig. 3. Density oscillation in the plasma grating accelerator.

3. Acceleration in Plasma Waves

In this section we consider the PBWA as an accelerating system and discuss some dynamic aspects of an accelerated electron bunch. The basic layout for PBWA is shown in Fig. 4. In order to make optimum use of the laser beam it is necessary to match the Rayleigh length R to the acceleration section. Here we choose the section length L to be twice of R. This in turn determines the diffraction limited spot size, $a^2 = R\lambda/\pi = L\lambda/2\pi$. On the other hand, a relativistic electron beam is much less divergent, and is given by a radius b. According to Eq. (12) the acceleration gradient $e\mathcal{E}_z$ has a parabolic dependence on r, which induces an energy spread among particles at different radii after being accelerated for some distance. For high energy physics purposes, the final energy spread has to be limited to a small percentage. This can be insured if $b \ll a$. The accelerated beam is injected behind the laser beams at a proper phase such that it is both accelerated and focused (*cf.* Fig. 2).

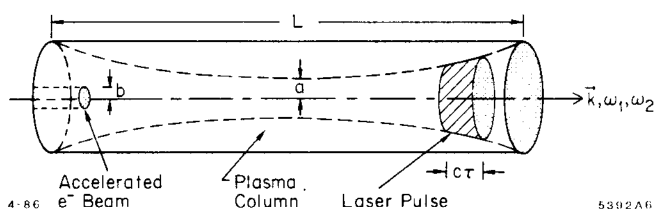

Fig. 4. A schematic layout of the PBWA.

3.1 The Betatron Oscillation

While accelerating, the driven beam will in general slip over the phase of the plasma wave. If this phase slippage is slow, then we can calculate the transverse focusing effects as if the beam were at a fixed phase on the wave.

The differential equation governing the transverse "betatron" oscillations of a highly relativistic particle is

$$\frac{d^2 r}{dz^2} = e\,\frac{\mathcal{E}_r}{\gamma mc^2} \quad , \tag{14}$$

where γmc^2 is the particle's instantaneous relativistic mass. For small radius from Eq. (12), we have

$$\frac{d^2r}{dz^2} = \left[\frac{\omega_p r e^2 E_0^2 \sin\phi}{4\gamma m^2 c^2 \omega^2 a^2}\right] r \quad , \tag{15}$$

where ϕ is the phase along the plasma wave that the driven beam locates. Identifying the coefficient of r above with β^{-2} yields the beta function:

$$\beta = \left[\frac{4\gamma m^2 c^2 \omega^2 a^2}{\omega_p r e^2 E_0^2 \sin\phi}\right]^{1/2} \quad . \tag{16}$$

3.2 Phase Slippage

Since the driven beam velocity is approximately c, whereas the plasma phase velocity is $c(1-\omega_p^2/\omega^2)^{1/2} < c$, the driven beam will slip along the plasma wave. From Eq. (6) the phase slippage in distance L is $\delta = (\omega_p^2/\omega^2)k_p L/2$. For a given phase slippage the plasma frequency is therefore determined by

$$\omega_p = \left[\frac{2\delta c\omega^2}{L}\right]^{1/3} \quad . \tag{17}$$

On the other hand, the driven beam sees a varying $e\mathcal{E}_z$ along L due to the phase slippage δ. The averaged value of $e\mathcal{E}_z$ is related to the ideal value by a form factor $\sin\delta/\delta$:

$$e\mathcal{E}_z^{\text{ave}} = \alpha mc\omega_p \left(\frac{\sin\delta}{\delta}\right) \quad , \tag{18}$$

where α is the fraction of the plasma density which is perturbed, *i.e.* $n_1 = \alpha n_0$. Maximizing $e\mathcal{E}_z^{\text{ave}}$, we find that $\delta \simeq 5\pi/16$.

From the above discussion we see that in PBWA the phase slippage is a non-negligible effect that influence the performance of the scheme. To avoid a large δ, two ideas have been introduced. The Surfatron[7] employes a transverse external magnetic field which forces the accelerated particles to "surf" around plasma waves. With proper arrangements, the beam could in principle lock into a fixed phase. The Plasma Fiber Accelerator,[8] on the other hand, tries to increase the phase velocity of the beat wave to near c. This is achieved by creating a duct structure in the plasma, in which the density is low inside and high outside such that the EM wave is evanescent, enabling the plasma beat wave phase velocity to be equal to any prescribed velocity within the channel.

4. The Laser Requirements

4.1 The Transverse Size

At the beginning of the previous section we defined our system with a diffraction limited laser spot size at the waist, $a^2 = R\lambda/\pi = L\lambda/2\pi$. In terms of a chosen phase slippage δ and eliminating the section length L, we can verify that

$$a^2 = \frac{2\delta\, c^2\, \omega}{\omega_p^3} \quad . \tag{19}$$

Notice that the effect of Rayleigh diffraction diminishes when the laser beam reaches the threshold power,[12]

$$W_c \simeq \frac{2\pi}{3}\, n_0\, mc^2 \left(\frac{c}{\omega_p}\right)^2 \left(\frac{\omega}{\omega_p}\right)^2 \quad . \tag{20}$$

When above the threshold, the laser beam would exhibit relativistic self-focusing effect during propagation through a plasma. This occurs because the electrons near laser beam axis are the ones being driven the hardest, which acquire higher relativistic masses and therefore result in higher laser group velocities (*cf.* Eq. (6)). From Computer simulation[13] it is found that the laser beam will focus down to a radius $\sim c/\omega_p$ asymptotically. One obvious merit for employing the relativistic self-focusing effect in PBWA is to extend the Rayleigh length substantially. But there are shortcomings. It is not clear whether a system can be properly arranged such that only self-focusing, and no filamentation occurs to the laser beam. In addition, the strong radial gradient of a focused beam provides a ponderomotive force which blows plasma out of the channel in a time as fast as one ion plasma period, necessitating the use of laser pulses shorter than this. In turn this invokes a stringent constraint on the necessary laser power. To avoid these subtleties we still confine ourselves in a Rayleigh diffraction dominated regime for the remaining discussions.

4.2 The Laser Energy

The laser beam power for the beam profile given in Eq. (2) is $W = (\pi a^2/2)E_0^2 c/8\pi$. If we assume that we have a laser pulse length τ, the energy necessary to drive the plasma to $n_1 = \alpha n_0$ is[14]

$$W\tau = \frac{\alpha\delta m^2 c^5}{e^2\omega_p}\left(\frac{\omega}{\omega_p}\right)^3 \quad . \tag{21}$$

4.3 The Efficiency

The overall efficiency of the PBWA can be divided into three parts. The first part is the efficiency of conversion of "wall plug" energy to laser energy, which will not be discussed here. The second efficiency is the conversion of laser energy to plasma energy. The third efficiency is that for conversion of the plasma energy to the driven electron beam.

The energy stored in the plasma can be easily derived by multiplying the energy density by the volume: $P.E. = (\mathcal{E}_z^2/8\pi)(\pi a^2/2)L$. Substituting from Eqs. (17) and (19), and using the relation $e\mathcal{E}_z = \alpha m c\omega_p$, we find

$$\eta_1 = \frac{P.E.}{W\tau} = \frac{\alpha\delta}{4} \quad . \tag{22}$$

Take $\delta \simeq 5\pi/16$, and $\alpha = 0.25$, which is approximately the saturation value,[15] $\eta_1 \simeq 0.06$. If laser pump depletion is included in the analysis, this number will be reduced slightly.

The third efficiency is that from the plasma to the driven bunch. The total acceleration gradient experienced by a bunch with N_2 particles in a plasma wave is

$$G \equiv \frac{dE_2}{dz} = e\mathcal{E}_z^{\text{ave}} - 4e^2\,\frac{N_2}{b^2} = e\mathcal{E}_z\left(\frac{\sin\delta}{\delta}\right) - 4e^2\,\frac{N_2}{b^2} \quad . \tag{23}$$

The second "beam loading" term is due to the plasma wake induced by the trailing bunch. The efficiency is given by the total energy gained of the bunch divided by the plasma energy,

$$\eta_2 = N_2\,GL\left(\frac{\mathcal{E}_z^2}{8\pi}\,\frac{\pi a^2}{2}\,L\right)^{-1} \quad . \tag{24}$$

This efficiency is maximized when $N_2 = (\sin\delta/\delta)\mathcal{E}_z b^2/8e$, and the value is given by

$$\eta_2^{\max} = \left(\frac{\sin\delta}{\delta}\right)^2\frac{b^2}{a^2} \simeq .72\,\frac{b^2}{a^2} \quad . \tag{25}$$

For example if we restrict the induced energy spread to 1%, then $\eta_2^{\max} \simeq 0.02$.

We see that both efficiencies η_1 and η_2 are quite low. There are, however, possible ways to improve them. To improve η_1 one possibility is to reuse the laser beam, which is not been pump depleted too much, after a suitable amplification. This would yield a very high repetition rate.

As for improving η_2, one may consider modifying the radial intensity profile of the laser beam such that it is essentially constant. In doing so, the radial dependence of $\mathcal{E}_z$ would be much weaker, allowing for a much larger accelerated beam cross-section πb^2 limited by a given induced final energy spread. A similar consideration was discussed in Ref. 9.

5. Numerical Examples

Now we come to specific examples of the PBWA. As mentioned earlier, our guide is the self consistency among all relevant accelerator parameters within the scheme. Our approach is to choose a set of parameters that we fix from the beginning. The remaining parameters can then be calculated in terms of those chosen ones using the formulas derived previously. To make meaningful examples we employ only those lasers and electron beams that are presently available. Therefore we need to fix the laser frequency ω by choosing a particular laser source. If we further fix the section length L, the phase slippage determines the plasma frequency ω_p. This means that $\mathcal{E}_z$ is a derivable quantity.

To keep the dimensions to a laboratory scale, we select the acceleration lengths to be 10 cm and 100 cm. These two lengths are then combined with two different laser frequencies, the N_d: Glass and the CO_2 laser, to form four sets of sample

Table 1. **Plasma Beat Wave Accelerator**

Chosen Parameters	Values			
ω [sec^{-1}]	Nd: Glass	1.78×10^{15}	CO_2	1.78×10^{14}
L [cm]	10	100	10	100
α	0.25	0.25	0.25	0.25
δ [rad]	$5\pi/16$	$5\pi/16$	$5\pi/16$	$5\pi/16$
$\sin\delta/\delta$	0.85	0.85	0.85	0.85
$\omega_p\tau$	1000	1000	1000	1000
Derived Parameters				
ω_p [10^{13} sec^{-1}]	2.65	1.23	.571	.265
n_0 [10^{16} cm^{-3}]	21.7	4.67	1.00	0.22
$e\mathcal{E}_z$ [GeV/m]	9.38	4.36	2.00	0.94
a [mm]	0.13	0.41	0.41	1.30
a/λ_p	1.82	2.70	1.25	1.82
β [$\sqrt{\gamma/\sin\phi}$ mm]	0.18	0.57	0.57	1.80
N [10^{10}]	$1.95\eta_2$	$9.04\eta_2$	$4.19\eta_2$	$1.95\eta_2$
W_T [J]	23.9	515.4	11.1	239.2

6. Experimental Progress

The first experimental verification of the theoretical concepts that we described so far was performed at UCLA.[16] The 9.6 μm and 10.6 μm lines of a CO_2 laser were used to resonantly drive a plasma of density 10^{17} cm^{-3}. The conclusive evidence for the existence of high phase velocity plasma wave excited by the beating of the two laser lines comes from ruby laser Thomson scattering. The scattering angle is adjusted to k match to the fast plasma wave. By moving the fiber optics which collects the scattered light on a shot-to-shot basis, the k spectrum of the plasma wave has been obtained. Figure 5(a) shows that $\Delta k = k_p$. In addition, Fig. 5(b) shows the frequency shift of the ruby light from the stray position to be exactly $\Delta\omega = \omega_p$. These measurements unambiguously identify the wave as being the plasma beat wave.

From Δk and the plasma density perturbation measured, it was inferred that a longitudinal electric field between 1 GeV/m and 3 GeV/m was achieved.

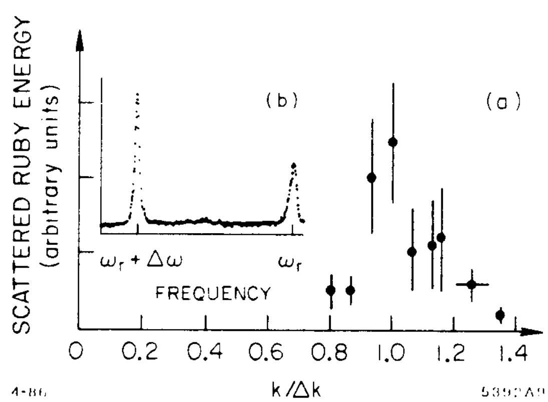

Fig. 5. (a) The k spectrum, and (b) the frequency shift, from the UCLA experiment.

7. Summary

Substantially progress has been made on laser plasma accelerators in recent years. Among them the Plasma Beat Wave Accelerator is best developed. Theoretical and computational studies of the subject are now complemented by experimental results at UCLA. Other experimental efforts are also under way, for example, at Rutherford Appleton Laboratory, and at Québec, Canada.

This paper analyzes the PBWA from a systematic view point. The parameters we derived are suitable for laboratory test-of-principle experiments, or one stage of a real world future accelerator. The consideration is to limit the plasma oscillation within the linear regime, and various nonlinear effects can be avoided. Under this condition it is found that the laser energetics requirements are high, but still within technological limits.

However, for laser plasma accelerators to be successful candidates for a future accelerator, it is essential that the "wall plug" efficiency to produce the laser power be much improved. This, unfortunately, lies outside the scope of this paper.

References

1. *Laser Acceleration of Particles*, Los Alamos, 1983, ed. Channell, P. J., AIP Conference Proceedings No. 91.
2. *Laser Acceleration of Particles*, Malibu, 1985, ed. Joshi, C. and Katsouleas, T., AIP Conference Proceedings No. 130.
3. For a review, see Katsouleas, T. *et al.*, ibid. Ref. 2.
4. Tajima, T. and Dawson, J. M., *Phys. Rev. Lett. 43*, 267, 1979.
5. Katsouleas, T., Dawson, J. M., Sultana, D. and Yan, Y. .T., *IEEE Trans. Nucl. Sci. NS-32*, 3554, 1985.
6. Tajima, T., *Proceedings of International Accelerator Conference*, Fermilab, 1983, pp. 470.
7. Katsouleas, T. and Dawson, *Phys. Rev. Lett. 51*, 392, 1983.
8. Chen, P. and Ruth, R. D., ibid. Ref. 2.
9. Ruth, R. D. and Chen, P., in *SLAC Summer Institute on Particle Physics,* Stanford, California, 1985.
10. Tang, C. M., Sprangle, P. and Sudan, R., *Appl. Phys. Lett. 45*, 375, 1984.
11. Darrow, C., Umstadter, D., Katsouleas, T., Mori, W. B., Clayton, C. E. and Joshi, C., UCLA preprint, April, 1986. Also submitted to *Phys. Rev. Letts.*
12. Max, C. E. and Arons, J., *Phys. Rev. Lett. 33*, 209, 1974.
13. Joshi, C., Mori, W. B., Katsouleas, T., Dawson, J. M., Kindel, J. M. and Forslund, D. W., *Nature 311*, 525, 1984.
14. Ruth, R. D. and Chao, A. W., *ibid.*, Ref. 1.
15. Rosenbluth, M. N. and Liu, C. S., *Phys. Rev. Lett. 29*, 701, 1972.
16. Joshi, C., Clayton, C. E., Darrow, C. and Umstadter, D., *ibid.*, Ref. 2.