A SIDE-INJECTED-LASER PLASMA ACCELERATOR

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ABSTRACT:

A new method for driving relativistic plasma waves capable of ultra-high acceleration gradients (order 1GeV/cm) is presented. By injecting a single laser frequency from the side, rather than colinearly with the accelerated particles, both pump depletion and particle dephasing may be avoidable. The coupling of the side injected laser to the relativistic plasma wave via a pre-formed density ripple in the plasma is modelled analytically and with computer simulation.

INTRODUCTION:

Present laser schemes for realizing the ultra-high gradients possible in plasma space charge waves (order 1GeV/cm.) are generally colinear and suffer from the problem of pump depletion.[1-4] That is, the laser continually feeds its energy to plasma waves which, although having high phase velocity, have low group velocity and hence leave their energy behind.

In this paper, we present a side-injected-laser scheme which enables the laser energy to be resupplied along the length of the accelerator. Only one laser frequency is needed for this scheme, and the phase velocity of the excited plasma waves can be controlled along the accelerator. Thus, both pump depletion and particle dephasing can be avoided.

The basic ideas is illustrated in Fig. 1. Laser radiation of frequency ω_o is incident approximately perpendicular to the axis of a long column of plasma. The plasma is of average density n_o such that the plasma frequency ω_p ($\omega_p{}^2 = 4\pi n_o e^2/m$) is slightly below ω_o and contains a neutral density ripple of wavenumber k_r along the plasma axis. Such a ripple might be produced by launching an ion acoustic wave in the plasma or by ionizing a grating to form the plasma. If the laser is polarized along the plasma axis, a quisiresonant coupling between the laser and the ripple drives a plasma space charge wave with phase velocity ω_o/k_r along the axis.

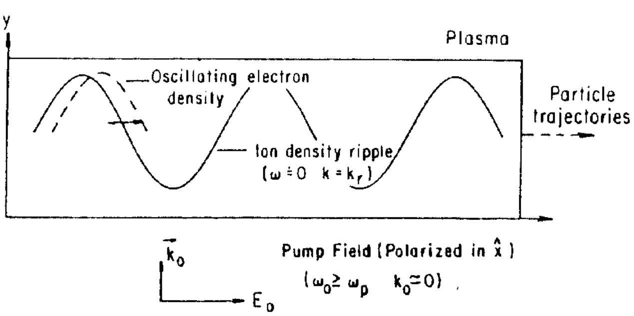

Figure 1. A laser polarized along a preformed plasma density ripple wiggles electrons to produce a relativistic space charge wave.

This scheme somewhat resembles the so called near field laser acceleration schemes which use a grating to couple laser energy to accelerated particles.[5] Here the role of the grating is played by the plasma density ripple (with the advantage that the plasma is already ionized and cannot be destroyed by the laser fields).[6] The plasma dynamics are similar to the quasiresonant mode coupling between long wavelength plasma waves and ion acoustic waves[7], and also to parametric decay.[8]

The coupling of laser energy to longitudinal wave energy via the ion acoustic or density ripple can be viewed as a three-wave process. The vector addition of the wave energy-momentum 4-vector of the laser (ω_o, k_o) plus that of the ripple ($\omega_{ac} \approx 0$, k_r) equals that of the plasma wave (ω_p, k_p):

$$\begin{aligned} \omega_o \pm \omega_{ac} &\approx \omega_p \\ \underline{k}_o \pm \underline{k}_r &\approx \underline{k}_p \end{aligned} \tag{1}$$

Since ω_o must be greater than ω_p in order to propagate in the plasma ($k_o{}^2 = [\omega_o{}^2 - \omega_p{}^2]/c^2$ is the dispersion relation for light in a plasma), these equations can only be satisfied approximately (hence the term quasiresonant coupling). If we take ω_o as close to ω_p as possible while still allowing propagation, the dispersion relation for light waves indicates that k_o will be small and k_p will lie approximately along the $\hat{k}_r$ axis. The gradient in plasma density which often occurs in the $\hat{y}$ direction will further facilitate propagating the laser into the ripple.

The plasma velocity of the resulting plasma wave is evidently from (1)

$$V_{ph} = \frac{\omega_p}{k_p} = \frac{\omega_o + \omega_{ac}}{|k_o \pm k_r|} \approx \frac{\omega_o}{k_r}$$

where we have assumed ω_o near ω_p so that $k_o \approx 0$.

By slightly varying the ripple wavelength (λ_r) in such a way that $\lambda_r(x) = 2\pi v(x)/\omega_o$ where $v(x)$ is the velocity of an accelerating particle ($\approx c$), the phase velocity can be adjusted to match the accelerating particles. Alternatively, the particles might be surfed[3] (phase locked by an imposed DC magnetic field).

The small amount of angle in $\vec{k}_p$ relative to the plasma axis can be compensated for by angling the wavefronts of the density ripple as shown in Fig. 2. Alternatively, one might inject lasers from both sides of the plasma and accelerate down the symmetry axis of the converging plasma waves that result.

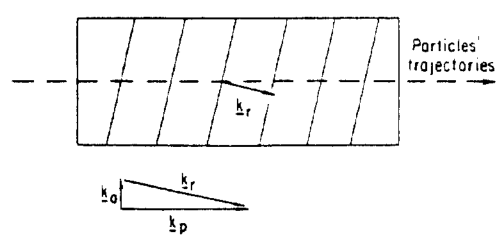

Figure 2. Angled ripples enable k_p along axis.

THEORY:

We may describe the growth and saturation of the plasma wave by a simple cold fluid model. Consider a neutral, rippled plasma of density $n(x) = n_o + \delta n \sin k_r x$. Linearizing the electron plasma density as $n = n_o + \delta n(x) + n_1(x,t)$ and velocity $v_x = v_o + v_1(x,t)$, where $v_o = (-eE_o/m\omega_o)\cos\omega_o t \equiv -v_{os}\cos\omega_o t$, we obtain for the momentum and continuity equations:

$$\frac{\partial v_1}{\partial t} + v_o \frac{\partial v_1}{\partial x} = \frac{-e}{m} E_1 \tag{2}$$

$$\frac{\partial n_1}{\partial t}+\partial_x[(n_o+\delta n \sin k_r x+n_1)(v_1-v_{os}\cos\omega_o t)] = 0 \quad (3)$$

Subtracting the spatial derivative of (2) from the time derivative of (3), we obtain a wave equation for the electron plasma wave density:

$$\frac{\partial^2}{\partial t^2}(n_1/n_o)+\omega_p^2(n_1/n_o) = \quad (4)$$
$$(\frac{1}{2})\omega_p^2(\delta n/n_o)(v_{os}/c)\{\sin(\omega_o t-k_r x)+\sin(\omega_o t+k_r x)\}$$

where we have kept only the lowest order terms (assuming $\delta n/n \ll 1$, $v_{os}/c \ll 1$), and we have used Poisson's equation for $\partial E_1/\partial x = -4\pi e n_1$.

Each term on the right hand side of (4) represents a driver for the plasma wave which is analogous to the pondermotive force term in the beat wave excitation scheme. In fact, equation (4) whould be just like that of the laser beat excited plasma waves with the replacement of $\delta n/n_o$ with v_{os}/c of the second laser and the inclusion of the relativistic correction to $\omega_p{}^2$ $[\omega_p{}^2 + \omega_p{}^2\ (1-(3/8)(n_1/n_0)^2)]$[9]. The present case differs in that here both left and right going plasma waves are excited.

Initially, since $\omega_o \approx \omega_p$, each wave exhibits the secular growth of a resonantly driven harmonic oscillator:

$$\varepsilon = \frac{(v_{os}/c)(\delta n/n_o)}{4}\ \omega_p t \quad (5)$$

where ε is the amplitude of n_1/n_o. The corresponding electric field amplitude associated with the plasma space charge waves is from Poisson's equation:

$$E \approx 4\pi e n_1/k_r \approx \varepsilon\sqrt{n_o}\ \text{V/cm}$$

where n_o is in units of cm^{-3}.

The growth of the plasma wave will be limited by the onset of any of the following three mechanisms. First, the plasma wave cannot grow beyond the amplitude corresponding to wavebreaking[10] or trapping of the background plasma; namely[1]:

$$\varepsilon \lesssim 1 - \sqrt{3}\ V_{th}/c - 1/\gamma_{ph} \quad (6a)$$

where V_{th} is the plasma thermal velocity and $\gamma_{ph} = (1-V_{ph}{}^2/c^2)^{-1/2} \gg 1$.

Second, the detuning between the laser at ω_o and the plasma at ω_p will stop the wave growth after a time $(\omega_o - \omega_p)t \approx \pi$ at which time

$$\varepsilon \lesssim \frac{(v_{os}/c)(\delta n/n_o)}{2(\omega_o/\omega_p-1)} \quad (6b)$$

Finally, if ω_o is very close to ω_p, then the relativistic frequency shift of the plasma wave may dominate the detuning. In analogy with the beat wave[9], the relativistic detuning will cause saturation at

$$\varepsilon \leq \left(\frac{16}{3}\frac{v_{os}}{c}\frac{\delta n}{n_o}\right)^{1/3} \quad (6c)$$

The actual saturation amplitude will then be governed by the smaller of Eqs. (6a-c).

SIMULATION:

The mechanisms described in the previous sections have been studied with one-and-three-halves dimensional (i.e., x, v_x, v_y, v_z) particle-in-cell simulation codes. The simulations illustrate the growth and saturation of the plasma waves and demonstrate subsequent acceleration of particles injected along the ripple direction. In all simulations, the density ripple is initially sinusoidal, ions are immobile, the imposed electric field is of the form $\vec{E} = \hat{x}\ E_o \sin\omega_o t$ ($k_o = 0$) and periodic boundary conditions are used.

In Fig. 3, we show the growth of the plasma wave (ε) in time at a fixed x position for a simulation with $\delta n/n = .2$, $v_{os}/c = .1$, $\omega_o = 1.01\ \omega_p$. The theoretical growth rate from Eq. (5) is shown for comparison (actually the growth rate plotted is twice Eq. (5) since ε represents the sum of both left and right going waves). The wave detuning and subsequent decrease in amplitude after time $50\omega_p{}^{-1}$ is visible in the figure. The saturation amplitude is about 50% smaller than predicted by Eq. (6c).

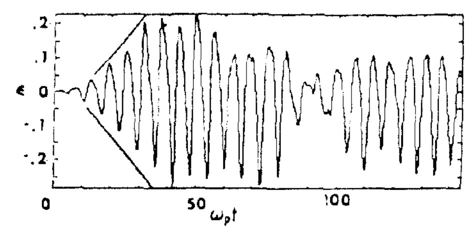

Figure 3. Plasma wave growth, ε vs. t at fixed x in 1-D simulation. Straight lines are linear theory.

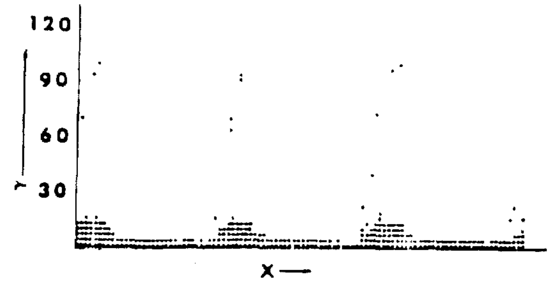

Figure 4. Particle energy γ vs. x.

In Fig. 4, we show the energy gained by injected electrons in another simulation ($\omega_o = 1.1\omega_p$, $v_{os}/c = .37$, $\delta n/n = .2$, $\omega_o/k_r = .996c$). The electrons have gained energy from $\gamma = 1.3$ to $\gamma \approx 100$ in a distance 380 c/ω_p (approximately .6mm for CO_2 parameters). The particles in Fig. 4 have reached their maximum energy as determined by the length over which they dephase (outrun) from the wave (the BWA limit[4]: $\Delta\gamma \approx 2\varepsilon\gamma_{ph}{}^2$, approximately 90 for this case).

In principal, higher energies can be reached by increasing the ripple spacing to speed up the wave or by surfing the particles across the wavefronts. In Fig. 5, we have applied a DC magnetic field B_o in the $\hat{z}$ direction in order to test the surfatron phase locking mechanism[3]. The ripple and laser parameters were chosen such that $\gamma_{ph} \approx 3.2$, $\varepsilon \approx .5$. The maximum energy gain for such a case without phase locking (B_o=0) would be from above: $\Delta\gamma \approx 10$. In Fig. 5, the particles are phase locked and have already gained three times this dephasing limit.

The simulations provide insight into some interesting self-consistent effects. In Fig 6a, we show the plasma space charge field E vs. x at time $48\omega_p{}^{-1}$ in a surfatron run (ω_c/ω_p=.01, $\gamma_{ph} \approx 10$, v_{os}/c= .12, $\delta n/n$=.1). The wave field amplitude is roughly

$\varepsilon \approx .21$ at this time and peaked at $\varepsilon \approx .38$; the theoretical values from Eqs. (5) and (6c) are $\varepsilon = .29$ and .4, respectively.

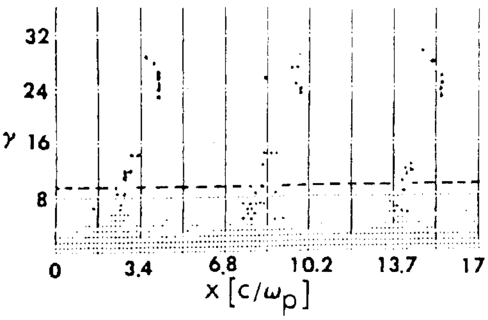

Figure 5. γ vs. x in a surfatron run ($\gamma_{ph}=3.2$) and energy limit without phase locking (dashed).

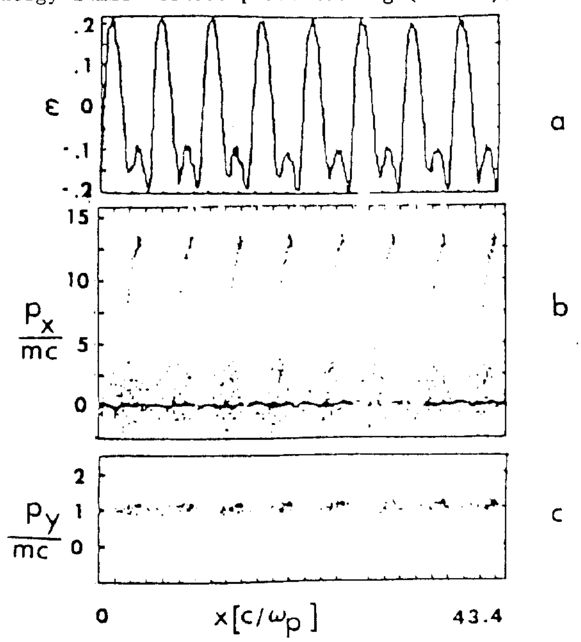

Figure 6. a) ε vs. x at $\omega_p t=48$, b) p_x vs. x and c) p_y vs. x at $\omega_p t=120$ in a surfatron run.

Secondary peaks at the trough of each wave are distinctly visible in the figure. These are due to the space charge fields of trapped particles. Although injected uniformly with only.1% of the background plasma density, it is clear from the phase space figures (6b & c) that they have become bunched in each of the plasma waves. Note also that the ratio of momenta p_y/p_x is near the asymptotic surfatron value of $1/\gamma_{ph}$ (from $p_y/p_z \approx V_y/V_x \approx (c^2-V_x{}^2)^{1/2}/V_x$ and $V_x \approx V_{ph}$).

DISCUSSION

One readily conceivable way to experimentally verify the wave excitation and acceleration mechanism would be to use a CO_2 laser prepulse to ionize a solid target upon which was etched a grating of ten micron periodicity[11]. This would produce a rippled plasma. A second pulse which contained a few millijoules in the first couple of picoseconds of its rise could then accelerate electrons from the background plasma to up to 10MeV in .5 mm.

The realization of the present scheme as a full scale accelerator faces several technological hurdles. Requirements on the acuracy of the density ripple spacing are severe. A practical way of sweeping the laser energy along the system must be developed (such as that depicted in Fig. 7). Without sweeping the laser energy, the length of each stage would be limited by the onset of ion motion to be about (M_i/m) plasma wavelengths (where M_i is the ion mass).

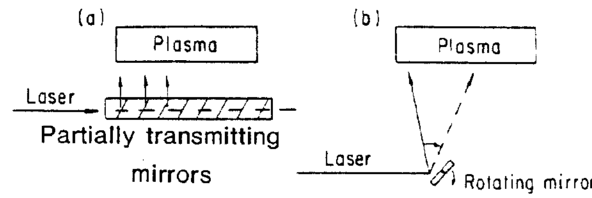

Figure 7. 2 possible means of sweeping laser energy.

A number of physics issues remain to be studied. For example, the effect of the pondermotive force caused by the finite width of the lasers is of interest, as are ripple decay times and finite k_0 effects. The potential advantages of this scheme--ultra-high gradients, avoidance of pump depletion and particle dephasing, and the use of a single frequency laser--make these issues worth pursuing.

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