# Theory and Simulation of Plasma Accelerators

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*Abstract*

We report on some of the recent theoretical and computational results at UCLA and USC on plasma-based accelerator concepts. Topics discussed include beat-wave excitation from short-pulse lasers, self-trapped electron acceleration from self-modulational instabilities and wakefield excitation in preformed channels.

## INTRODUCTION

For some time now plasma structures have been considered as the basis for future accelerators. The plasma serves two purposes: (1) the plasma has no breakdown limits because it is already ionized and (2) the plasma supports large longitdinal waves. In these waves the electrons oscillate back and forth at $\omega_p \equiv (4\pi e^2 n/m)^{1/2}$ due to the space charge of the immobile ion background irrespective of the wavelength. Therefore by properly phasing these oscillations it is possible to create a wave with $v_\phi \cong c$, i.e., a relativistic plasma wave. In such a wave electrons can acquire relativistic energies before they dephase from the wave. The accelerating gradient of a relativistic plasma wave is given by $\varepsilon\sqrt{n}\ V/cm$ where $n$ is the plasma density in $cm^{-3}$ and $\varepsilon$ is the density perturbation of the wave. For a density of $10^{16}$ $cm^{-3}$ gradients of 10 GeV/m are possible in a plasma.

Relativistic plasma waves can be generated by propagating either intense laser beams[1] or intense particle[2] beams through a plasma. During the past two years there have been several exciting experimental results on laser beam excitation,[3,4,5] so in this brief report we limit the results to those related to laser-plasma accelerators.

In 1979, Tajima and Dawson[1] published the seminal paper on laser-plasma accelerators. They showed that relativistic plasma wave wake is excited behind a short pulse with a pulse length matched to half a plasma wavelength, $L_p = \pi c/\omega_p$. This is now called the Laser Wakefield Accelerator (LWFA).[6] In addition, Tajima and Dawson suggested two alternative ways to excite a plasma wave: 1) use two longer pulses with a frequency separation equal to $\omega_p$ to resonantly excite a wave or 2) rely on a long pulse to undergo the Raman forward scattering instability.[7] The first is now called the Plasma Beat Wave Accelerator (PBWA) and the second is related to a scheme named the self-modulated LWFA.[9] We will present some results related to each scheme.

## PBWA

Theory,[8] simulations[8] and experiments[3] make it poignantly clear that the PBWA will work best for pulse lengths matched to the Rosenbluth and Liu detuning time and less than an ion period. Laser technology now makes it possible to generate pulses which satisfy these constraints for plasma densities above $10^{16}$ $cm^{-3}$. Based on these considerations, we have investigated the feasibility of a 1 GeV PBWA experiment using existing technology.[10] The proposed parameters are given in Table I. The parameters were modeled

| | |
|---|---|
| Laser wavelengths | 1.05 μm and 1.06 μm |
| Plasma Density | $10^{17} cm^{-3}$ |
| Plasma Source | Multiphoton Ionization |
| Laser Pulselength | 4 ps |
| Laser Power | 14 TW |
| Laser Spot Size (2σ) | 200 μm |
| Rayleigh length ($Z_R$) | 3.1 cm |
| Plasma Homogeneity | ± 7% |
| Peak Plasma Wave Amplitude | 0.5 |
| Peak Gradient | 160 MeV/cm |
| Final Energy | 1 GeV |

**TABLE 1.**

using a combination of simulation codes. In Fig. 1a we plot the peak accelerating wave amplitude as a function of axial position. These amplitudes were obtained by integrating the Rosenbluth and Liu envelope equations for each local position
within the focal cone of the laser. Treating each position locally has been verified in PIC simulations[8] as long as the spot size exceeds a few $c/\omega_p$. In Fig. 1b results from a 2-D PIC simulation which uses a prescribed ponderomotive force are presented. This simulation demonstrates that near the focus the plasma wave is nearly planar. The peak accelerating gradient corresponds to 15 GeV/m. In Figs. 1c and 1d we show the results from test particle simulations using the accelerating field of Fig. 1a. The injected beam is a 1 nC, 4 ps long continuous e-beam at an energy of 10 MeV with a spot size of 20 μm and an emittance of .1 mm-mr. The results show that $10^8$ (2% of the injected) electrons are accelerated into microbunches 30 fs long separated by 300 fs. To illustrate the evolution of these short laser pulses as they propagate through a Rayleigh length of plasma, we present results from a 1-D PIC simulation in Fig. 2. We show the accelerating field and the laser envelope after the laser has gone through a Rayleigh length (10 pulse lengths) of plasma. The plasma wave and the envelope look almost identical to their initial profiles. We end this section by noting that experimental design parameters can also be put forth for bunching electron beams at lower energies, e.g., 100 MeV.

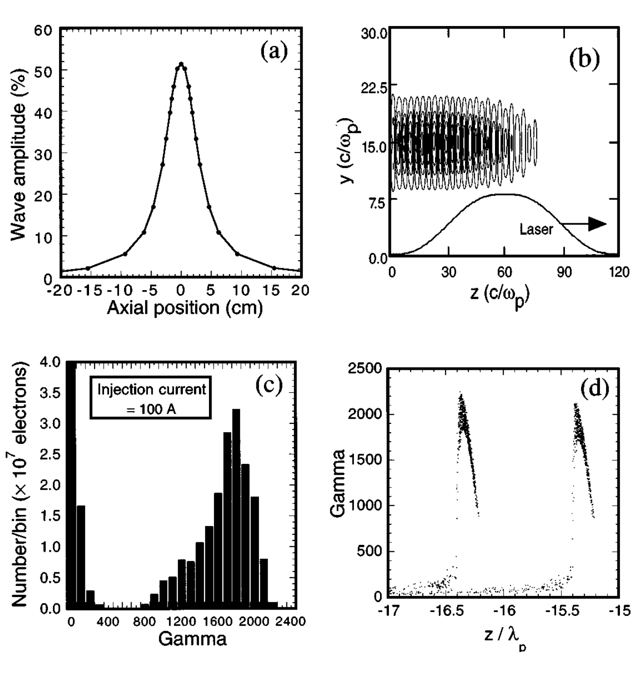


FIGURE 1. Simulation results for a possible 1 GeV PBWA experiment.

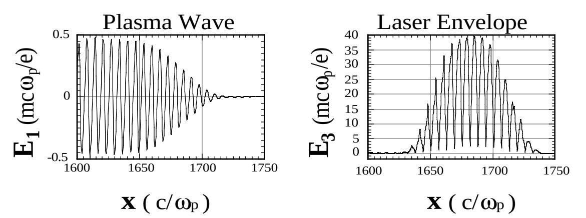


FIGURE 2. 1-D PIC simulation results of the 1 GeV design for a laser propagating through a Rayleigh length of plasma.

## SELF-MODULATED LWFA

It has been well known that beat wave excitation is related to a laser-plasma instability called Raman forward scattering (RFS).[1,7,13] However, RFS was not considered a serious accelerator concept because its growth rate was slow enough that ion motion disrupted the acceleration process. Simulations showed that this and wavebreaking led to inefficient acceleration and low beam quality.

The development of short-pulse lasers has led to new work and ideas for the use of laser instabilities. In 1992,Antonsen and Mora[15] and Sprangle[16] et al. demonstrated by using fluid codes that a short pulse high-intensity laser will self-modulate in a distance of a few Rayleigh lengths and generate large wakes. Recently, Krall et al.[9] and independently Andreev et al.[9], investigated the feasibility of using these wakes for an accelerator. Krall et al call this concept the self-modulated LWFA.

We have been investigating the stability of short-pulse lasers using particle-in-cell codes[12] rather than fluid codes. In addition we have been investigating the theoretical[13] differences between RFS of short-pulses and the self-modulation instability of Esarey et al.[12] For brevity we only present the simulations results while the theoretical results can be found in the references.[13] The simulations are done using a parallelized version of ISIS with a moving grid. These improvements make it possible for the first time to simulate the actual spatial and temporal scales of a laser-plasma accelerator experiment using a 2-D fully explicit PIC code.[4] The experimental parameters are $\lambda = 1\ \mu$m, $I = 10^{18}$ W/cm$^2$, $\tau_p = 600$ fs, $n \cong 1 \times 10^{19}$ cm$^{-3}$ and $W_o = 18\ \mu$m. These parameters are representative of both the LLNL[4] and RAL[5] laser systems. Typical simulations results are shown in Figs. 3 and 4. These results show that under most situations RFS of a short intense laser pulse inevitably leads to self-trapped electrons. In Figs. 3a and 3b the evolution of the laser pulse is shown. It is clear that the laser pulse breaks apart into beamlets spaced at the plasma wave wavelength in distances less than a Rayleigh length. This breakup is dominated by RFS as illustrated by the power spectrum in Fig. 3c which shows multiple stokes and anti-stokes sidebands. This beam breakup results in the plasma wave evolution depicted in Figs. 3d-g. The wave amplitude never reaches the cold wavebreaking value because it self-traps large amount of Raman back and sidescattered generated electrons. The electron distribution function is shown in Fig. 4 for two different propagation distances. Fig. 4a is representative of the LLNL interaction length while Fig. 4b is representative of the RAL interaction length. For the plasma density simulated, $n = 10^{19}$ cm$^{-3}$, the maximum electron energy saturates at ~ 60 MeV. These simulation results are in good quantitative agreement with the LLNL experimental results.[4] The exact RAL parameters have not yet been simulated. The PIC simulations clearly demonstrate that RFS and other self-modulational type instabilities can lead to self-trapped electrons generating a high current, 10 kA, poor beam quality electron beam. The experimentally inferred accelerating gradients are ~ 100 GeV/m.

## LWFA IN A HOLLOW CHANNEL

In any accelerator the energy gain is given by $q\int d\ell \bullet \vec{E}$. In plasma accelerators the gradient $qE$ can be very large but the interaction length $\int d\ell$ can be limited. One limitation is the diffraction length of the laser. To overcome this, methods for optical guiding are being actively investigated.[12] One method is to guide a laser pulse in a hollow plasma channel where the density at the channel wall is still much less than the critical density.[14] However, since the channel is completely evacuated, the plasma wave wake will not be excited in the same manner as in the conventional LWFA. We have investigated the wakes created

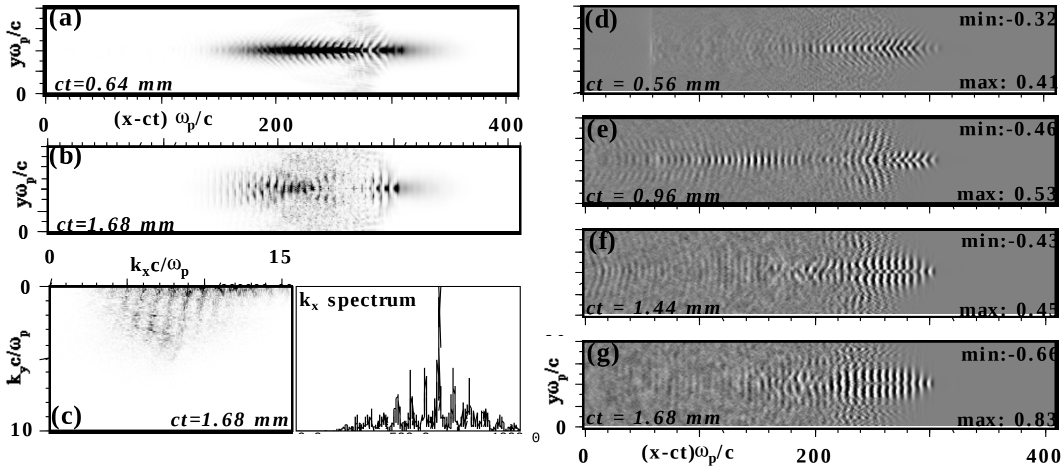


FIGURE 3. Results from a 2-D PIC simulation which models experiments at LLNL and RAL.

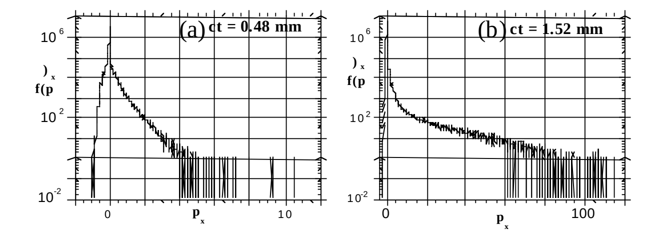


FIGURE 4. Distribution functons of the self-trapped electrons from the 2-D PIC simulation. P is normalized to mc.

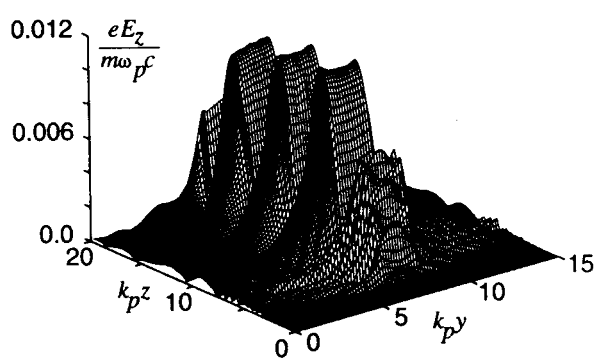

FIGURE 5. The accelerating wake generated by a short-pulse laser propagating in a hollow channel.

by a short-pulse, propagating in such a channel. The wake is supported by surface currents excited at the channel boundaries by the ponderomotive force of the laser. We find for sufficiently narrow channels that the accelerating gradient on axis is only slightly lower than that achieved in the conventional LWFA. Furthermore, the accelerating wake is uniform across the channel and the focusing wake varies linearly across the channel. These wake properties are advantageous for generating high quality beams. This is illustrated in Fig. 3 where the accelerating wake obtained in a PIC simulation is presented. The disadvantages of these scheme, (and other wakefield schemes in a channel), is that the wake is susceptible to resonance absorption at the channel walls. More details can be found in the references.

## CONCLUSIONS

We briefly review some of the recent work done at UCLA and USC on laser-plasma accelerators. This field has been bolstered by several laser-plasma experiments. Based on these results we believe it is possible to demonstrate in a PBWA experiment bunching of injected particles in the energy range of 100 MeV to 1 GeV using existing technology. Furthermore, single frequency excitation of wakes could form the basis of a robust, modest energy, ultra-high gradient but poor beam quality accelerator.

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