Final Scientific/Technical Report

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Florida A. and M. University

Electron Beam Transport in Advanced Plasma Wave Accelerators

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Accomplishments:

The goals of this research program include the study of the interactions among electron beams, laser beams and plasmas, for the purpose of developing an alternative, convenient, technique for studying the accelerating mechanisms of plasma wave accelerator devices. In particular, numerical simulations were used to design experiments to test the possibility that a low energy electron beam might be used to measure the large accelerating gradients of the plasma waves that are responsible for electrons being accelerated to very high energies over very short distances in plasma wave accelerator devices. The idea of the experimental test, that was modeled numerically, is to use an electron gun to produce a low energy, Gaussian cross-sectioned, electron beam, of energy in the 5 to 50 keV range, and to inject this electron beam perpendicularly across a plasma wave, which has large longitudinal electrostatic fields. The interaction of the electron beam with the plasma wave's large longitudinal electrostatic fields results in a distortion of the electron beam's original profile, which in turn, gives information on the properties of the plasma wave. A laboratory apparatus was assembled for the purpose of testing this idea and related schemes.

The goals include modeling the detailed interactions of individual electrons with the plasma wave and laser beams in such a way as to build up a very fundamental and graphical understanding of beam wave interactions that can be applied to many other situations. The model is based on solving the electron equation of motion using a leap-frog integration technique. The details of this model are described as follows.

This plasma wave is to be produced by intensely focusing a CO_2 laser beam into the plasma. The phase velocity of the plasma wave is relativistic and is determined by the relativistic velocity of the laser beams that produce the plasma wave. The plasma wave is represented in the simulation equations by its longitudinal and radial fields, E_z and E_r, respectively, for the longitudinal, z, and radial, r, directions. The expressions for these fields are those calculated for the beat-wave technique for exciting plasma waves, in which two CO_2 laser frequencies are injected co-linearly into, and beat within, the plasma. The natural frequency of the plasma is adjusted to match the lasers' beat frequency; thus a forced resonance condition exists which drives up, or excites, a plasma wave that moves along the direction of the two lasers. Some of the assumptions of the model are that the plasma wave fields, E_z and E_r, are specified and that their magnitudes have grown to their maximum values when the electrons cross the plasma wave. The number of electrons injected is very small in order to avoid beam loading, and the time the electron spends in the plasma wave is very short.

As the Gaussian profiled electron beam travels perpendicularly into the plasma wave, the direction of the electron velocity is perpendicular to the direction of the oscillating electrostatic fields of the plasma wave, as it speeds by relativistically. Therefore individual electrons get accelerated side to side and the amount of deflection that individual electrons experience differs, according to their position, or phase, relative to the plasma wave, and thus the direction and magnitude of the electrostatic fields they encounter. This results in a distortion of the original Gaussian profile, of the electron beam as it passes out of the plasma wave. The numerical simulations have shown that the amount of distortion of the electron beam profile increases directly as the amplitude as the plasma wave field increases. This leads to the suggestion that an electron beam injected in this way might be useful as a diagnostic of the plasma wave amplitude. These simulations also suggest that small amplitude plasma waves, or small changes in plasma wave amplitude, might be detectable using such an electron beam probe.

Figure 1 is a cartoon of the model showing a single electron injected into a plasma wave. Figure 2a is a simulation result of the trajectory of a single electron passing through a beat-wave plasma wave, generated by a two dimensional version of the simulation code. The electron is injected downward from the top of the figure and the plasma wave passes left to right, with its longitudinal electrostatic fields pointing along the same axis that the plasma wave moves, left to right. This longitudinal electrostatic field forces the electron to oscillate side to side. The radial width of the plasma wave is also Gaussian. As the electron enters the plasma wave, its side-to-side oscillation amplitude increases as the electron approaches the center of the wave, and decreases as it exits the wave. After the electron exits the wave, the end point of its trajectory has shifted in position along the direction that the plasma wave moves, and also it has an angular defection from its original direction. Figure 2b is the phase space plot (V_z vs z) for the trajectory in Figure 2a, which suggests that the orbits are closed, that energy is gained going in and energy is lost going out so that initial energy is equal to final energy, and that the electron has a net sideways drift which is in the direction of the plasma wave's electrostatic field, and propagation direction. The phase space plot of V_r vs r , for the radial direction, shows passing orbits as expected.

In figure 3 are plots of the electron beam profile (a) before it is injected into the plasma wave (Gaussian) and (b) after it exits the plasma wave (distorted). The electron beam is represented by thousands of individual electrons whose initial transverse positions relative to the beam axis are selected by bi-Gaussian random number generators. The electron positions along the beam axis are also randomly distributed, but using a uniform random number generation, simulating a short electron pulse. Due to the initial positions of the individual electrons, they will have different phases and will experience different electrostatic forces while traversing the plasma wave, resulting in their trajectories having different end points and angular deflections. The simulation code calculates the trajectories of each electron and their end points are plotted, as shown in figure 3b. The figure shows that the beam is spread out in the direction that the plasma wave moves. The average width of this distortion is measured and found to be directly proportional to the amplitude of the plasma wave longitudinal electrostatic field. There is also a radial electrostatic field due to the finite width of the plasma wave. This radial field results in some spreading in the direction perpendicular to the plasma wave. The magnitude of the radial field is large for narrow plasma waves, and small for wide plasma waves.

In this graphical study, many trajectories were calculated as a function of several different wave-particle interaction parameters, such as the plasma wave amplitude, the beat-wave wavelength combination, and the particle's energy, mass, injection phase and injection angle. As a result of these parameter variations, the trajectory end-shift and angle, and period of oscillation were observed. A small sample of these results are summarized in the two plots of Figure 4, which summarizes the shift in the trajectory vs plasma wave amplitude and vs electron beam energy. The parameter scalings summarized in these plots form the basis for suggesting that the electron beam can be used as a diagnostic tool, in several ways.

The above model was extended based on the ideal that remnants of the beat-wave laser beams that excited the plasma wave might co-propagate with the plasma wave after it is excited. Therefore, the electron would experience forces due to the oscillating plasma wave's electrostatic fields, as well as the oscillating lasers' electromagnetic fields. In the extended model, the frequencies of laser fields are higher than that of the plasma wave. Therefore it is expected that interference among the three waves would be expressed in the appearance of the electron trajectory. An example of this result is shown in figure 5, which is an overlay of the single electron trajectories for the plasma wave, the first CO_2 laser wave, the second CO_2 laser wave, and a trajectory for the superposition of these three waves. The simulation is two dimensional with both laser electromagnetic electric field vectors in the plane of the figure. On close inspection, there is evidence of interference in the combined trajectory.

This graphical study was further extended using a three-dimensional, relativistic version of the numerical code. Figure 6 is a sample plot of a short section of a 3-D trajectory of a single electron propagating across overlapping laser beams and a plasma wave. Also shown is a section of the corresponding phase space diagram.

The simulation codes developed during this research program are very flexible. It is noted that these simulation techniques can also be used to model many other advanced accelerator concepts, including the acceleration of proton and ions, electron injection schemes for acceleration, and radiation generation by the accelerated electrons. The simulations are run on Macintosh workstations using FORTRAN, IMSL, MATHEMATICA, and several graphics applications. A commercial particle-in-cell code, VORPAL, along with MATLAB, have been acquired and will be used to support our continuing research program, and benchmark the performance of our code.

Figure 7 is a schematic of the experimental apparatus that was built in the laboratory to attempt to test this model by measuring a plasma wave amplitude by injecting an electron beam across. The components of the experiment were selected to be appropriate for a small university laboratory, with rather low power and low energy capabilities. A new versatile rectangular vacuum chamber has been installed which is large and flexible enough to contain several diagnostic devices and optical components. A CO2 and a YAG laser are available for exciting, and diagnosing the plasma and plasma wave. A low power laser, laser profiler and emittance probes are available for performing measurements of the quality of the electron beam. Several other plasma, laser, and electron beam probes and devices are available. The experiment is pulsed so that fine-tuning of the triggering of the various components of the experiment is performed using pulse/delay generators. Although all of the component equipment has been operated separately, our continuing challenge is to operate the integrated system to test the results of the numerical models.

The graduate student working on this project is preparing these results for inclusion in his dissertation and in an article being submitted for publication in the Review of Scientific Instruments. Much more detail of these results are contrained in those documents.

FIGURES

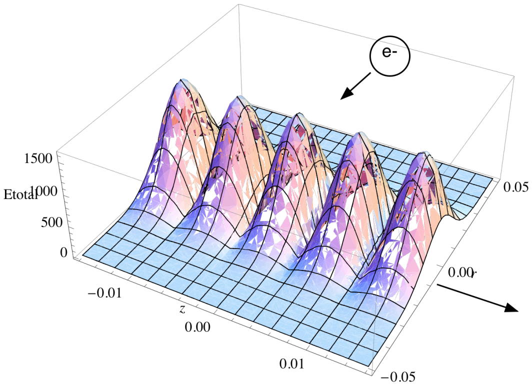
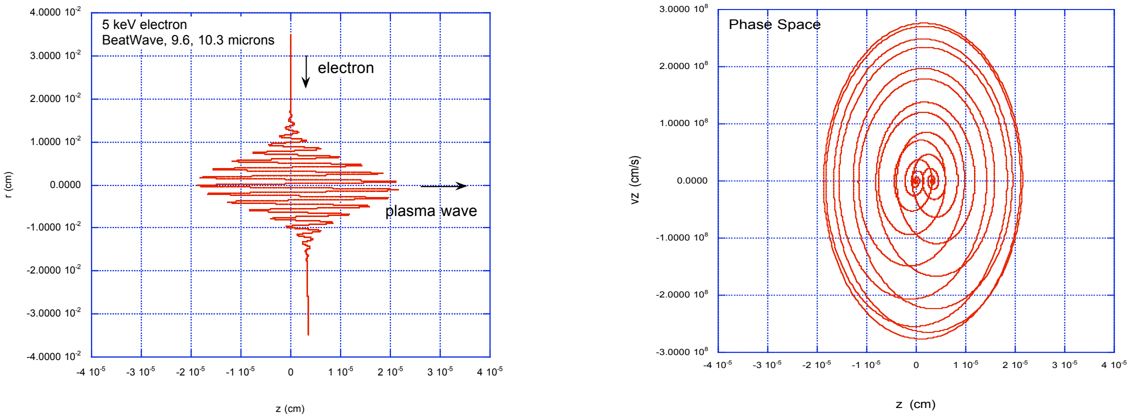
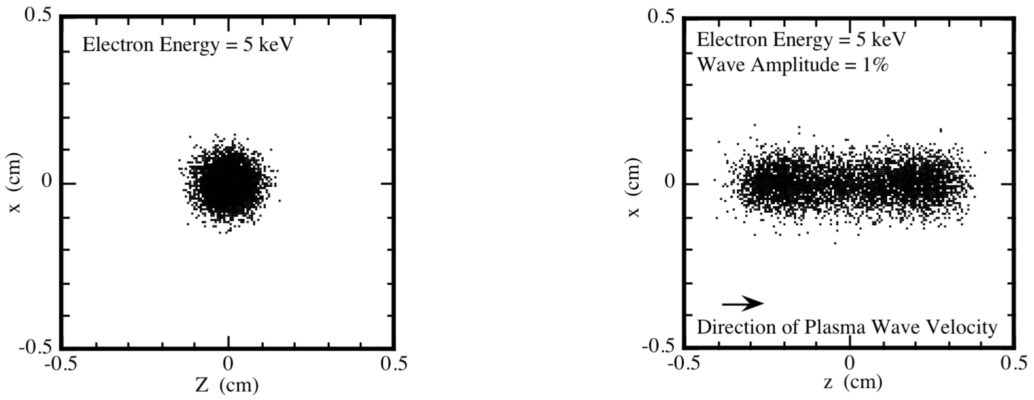


Figure 1-The geometry of the numerical model is based on the above cartoon, showing an electron injected into a plasma wave. The plasma wave moves to the right.



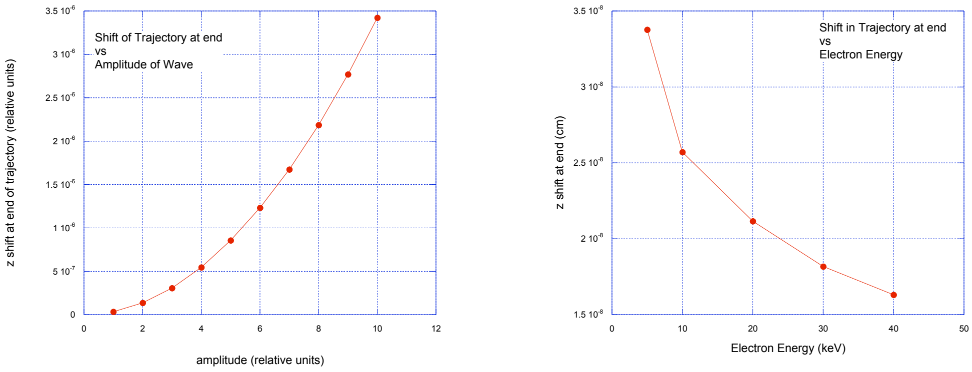
(a) (b)

Figure 2. (a) Trajectory of single electron through a plasma wave, showing drift and deflection angle. (b) Phase space plot of the trajectory, suggesting energy gain/loss and drift from the centerline at the end.



(a) (b)

Figure 3. The electron beam profile (a) before it is injected into the plasma wave (Gaussian) and (b) after it exits the plasma wave (distorted). The amount of distortion is proportional to the amplitude of the plasma wave. The beam moves out of the page.



(a) (b)

Figure 4: Sample scaling results. (a) Shift in trajectory vs plasma wave amplitude and (b) shift in trajectory vs electron beam energy.

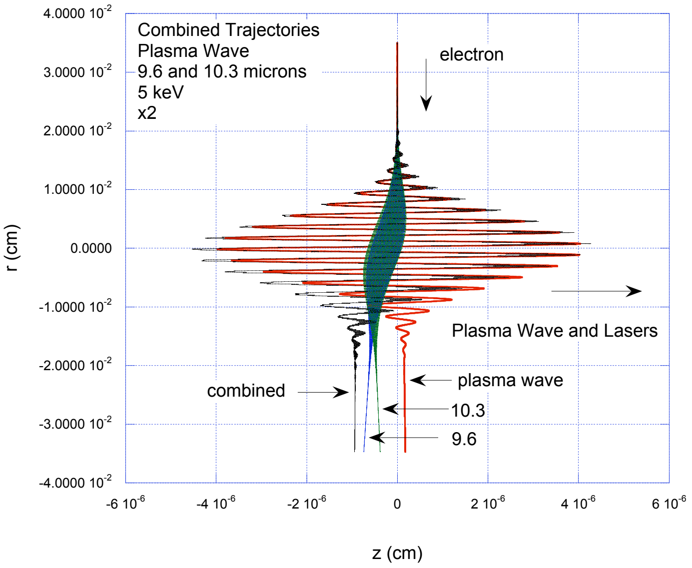
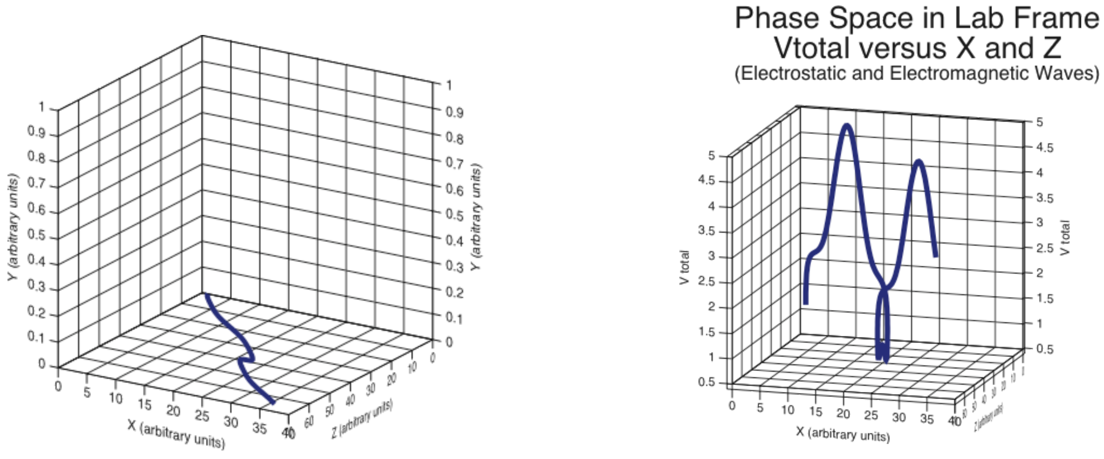


Figure 5: Example: An overlay of the single electron trajectories for the plasma wave, the first CO_2 laser wave, the second CO_2 laser wave, and a trajectory for the combination of these three waves. Exit drifts and angles vary widely depending on input parameters.



(a) (b)

Figure 6. (a) Sample 3-D trajectory of an electron propagating across overlapping laser beam and plasma wave. (b) Sample 3-D phase space diagram for electron propagating across overlapping laser beam and plasma wave, in the lab frame.

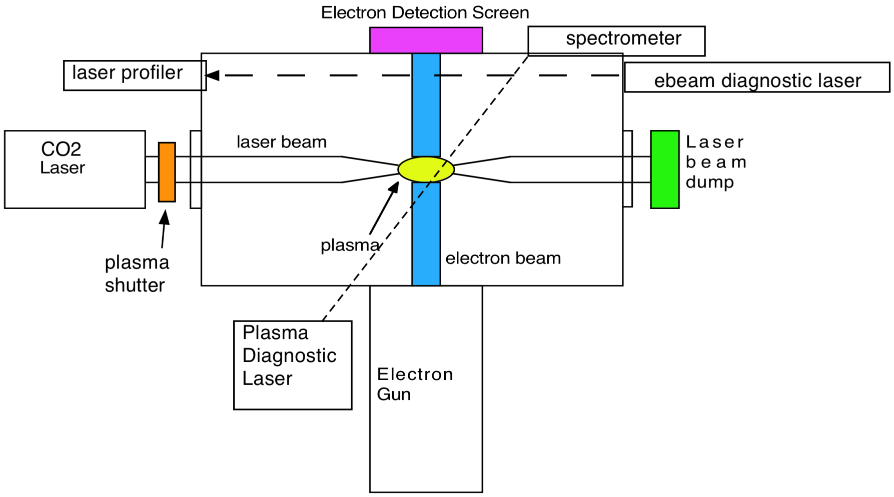


Figure 7. Conceptual arrangement of the experiment, showing major components and some of the detectors. The actual physical arrangement varies.

A list of papers and abstracts from 2009 to 2012:

"Numerical Study of Electron Trajectories in a Diagnostic for Relativistic Plasma Waves", A. L. Bowman and R. L. Williams, being submitted to Review of Scientific Instruments.

(Abstract) Arnesto Bowman and Ronald Williams, "A Fundamental Description of Electron Beam Plasma Wave Interactions", presented at the 15th Advanced Accelerator Concepts Workshop, June, 2012, Austin, TX.

(Abstract) R. L. Williams and A. L. Bowman, "Basic Study of a Diagnostic Electron Beam Traversing a Plasma and Electromagnetic Wave", presented at the International Conference on Plasma Science, June 2011, Chicago, IL.

(Abstract) Arnesto Bowman and Ronald Williams, "Basic Combination Analysis of Plasma Wave, Electromagnetic Wave, and Low Energy Electron Beams", presented at the 14th Advanced Accelerator Concepts Workshop, June 2010, Annapolis, MD.

(Abstract) Arnesto Bowman and Ronald Williams, "Basis Analysis of Electrons Crossing a Plasma Wave and Electromagnetic Wave", presented at the 52nd Annual Meeting of the Division of Plasma Physics, American Physical Society, November 2010, Chicago, IL.

Additional articles prior to 2009:

R. L. Williams, "Studies on Proton and Ion Interactions in Plasma-Based Collective Accelerators", Proceedings of the 2001 Particle Accelerator Conference, Chicago, p3972 (2001).

R. L. Williams and K. D. Gebre-Amlak, "Studies on the Interactions of a Probe Electron Beam with Relativistic Plasma Waves", Proceedings of the 1999 Particle Accelerator Conference, New York, p3681 (1999).

Students who worked on this research activity from 2009 to 2012:

One doctoral graduate student was fully supported by this grant during this period.

In previous years four other students have worked on this research project and received partial and full support. These students finished their graduate studies at other universities. Four students attended the US Particle Accelerator School. Several physics and engineering students did projects in the lab related to their classes in plasma physics and in laser physics. A high school physics teacher and his students did some projects in the lab during one summer session.