

FINAL TECHNICAL REPORT

Department of Energy Award Number: DE-SC0008157

Florida A. and M. University

ADVANCED ACCELERATORS: PARTICLE, PHOTON AND PLASMA WAVE INTERACTIONS

Ronald L. Williams, P.I.

Department of Physics

Florida A. & M. University

Tallahassee, Florida 32307

(ronald.williams@famu.edu, (850) 599-8383)

Date of Report: June 29, 2017

Period Covered by Report: August 1, 2012 to March 31, 2015

(Extension to March 31, 2017)

Tallahassee, Florida 32307

(ronald.williams@famu.edu, (850) 599-8383)

Abstract

“Advanced Accelerators: Particle, Photon and Plasma Wave Interactions”

AWARD NO. DE-FG02-12ER41834
(DE-SC0008157)

by

Dr. Ronald L. Williams, P.I., Physics Department
Florida A. & M. University (FAMU) (ronald.williams@famu.edu, (850) 599-8383)

The overall objective of this project was to study the acceleration of electrons to very high energies over very short distances based on trapping slowly moving electrons in the fast moving potential wells of large amplitude plasma waves, which have relativistic phase velocities. These relativistic plasma waves, or wakefields, are the basis of table-top accelerators that have been shown to accelerate electrons to the same high energies as kilometer-length linear particle colliders operating using traditional decades-old acceleration techniques. The accelerating electrostatic fields of the relativistic plasma wave accelerators can be as large as GigaVolts/meter, and our goal was to study techniques for remotely measuring these large fields by injecting low energy probe electron beams across the plasma wave and measuring the beam's deflection. Our method of study was via computer simulations, and these results suggested that the deflection of the probe electron beam was directly proportional to the amplitude of the plasma wave. This is the basis of a proposed diagnostic technique, and numerous studies were performed to determine the effects of changing the electron beam, plasma wave and laser beam parameters. Further simulation studies included copropagating laser beams with the relativistic plasma waves. New interesting results came out of these studies including the prediction that very small scale electron beam bunching occurs, and an anomalous line focusing of the electron beam occurs under certain conditions. These studies were summarized in the dissertation of a graduate student who obtained the Ph.D. in physics. This past research program has motivated ideas for further research to corroborate these results using particle-in-cell simulation tools which will help design a test-of-concept experiment in our laboratory and a scaled up version for testing at a major wakefield accelerator facility.

Description of Accomplishments

The overall objective of this project was to study the complex interactions among charged particle beams, photon beams and plasma waves in order to develop new and novel tools for advanced technology research and development, and for accelerator science. Our task was to design and develop new diagnostic techniques based on using low energy electron beams as probes of the plasma waves used for wakefield acceleration devices, and also to develop techniques for using low power lasers to diagnose and characterize particle beams. Numerical simulation tools were used to model the interactions, with the results used to help design apparatus for experimental confirmation in the university laboratory, and if successful, to test the diagnostic concepts at a larger wakefield accelerator center.

The numerical simulations of this study utilized the numerical parameters of experiments to accelerate electrons using the beatwave method of exciting relativistic plasma waves, that could be performed in a small university laboratory. A diagram of such an experiment is shown in figure 1, in which a CO₂ laser is used to provide the two beating wavelengths to excite the plasma wave, and an electron beam of energy 5-50 keV is injected perpendicularly to the plasma wave to probe its properties. The original experiment design used an eight-way cross as the vacuum/interaction chamber but it was too confining, and therefore was replaced with a large rectangular chamber, which was convenient for locating the various detectors and components inside and outside the chamber.

The simulations of the interactions of the electron beam with the plasma wave and laser beams involved solving the electron equation of motion with forces due to the plasma wave electrostatic fields and the laser beam electromagnetic fields, using codes that we wrote in FORTRAN. The single particle trajectory and phase space calculations were done in two-dimensions and were nonrelativistic. The multiparticle beam simulations were done in three-dimensions and were relativistic. We started with the 2-D single particle studies and examples of the trajectories and phase space of the electron interacting with the plasma wave only are shown in figure 2. The trajectory and phase space results varied as expected when the particle energy, mass, injection angle, and

plasma wave parameters were change during parameter studies. When the copropagating CO₂ laser beams were added, the trajectories and phase space results were modified as shown in figure 3. These results predicted enhanced deflection of the trajectories and interference patterns in the phase space diagrams. These phase space results suggest that this interference could be studied further in order to look for ideas to modify trapping and phasing to provide extended acceleration lengths and thus acceleration to higher energies by a single wave. These are ideas for further study.

The simulation of an electron beam was done by solving the relativistic equation of motion of as many as five thousand electrons in three dimensions, and with beam energies between 5 keV and 50 keV. A three-dimensional plot of the original positions of the electrons is shown in figure 4 (top plot) and the cross sections of the beam before (left plot) and after (right plot) passing through the plasma wave are shown. The original positions of the electrons were determined using Gaussian random number generators. These same random number generators can be used to set the beam initial emittance, energy spread, and Raleigh length (for modeling converging/diverging beams). The spreading of the beam shown in the figure after passing through the plasma wave is proportional to the amplitude of the plasma wave, and is the primary basis for this diagnostic technique. We note that the results of these studies of the interaction of an electron beam with electrostatic fields are compatible with much earlier results reported in the literature of experiments going back as far as 1900-1910. Next, this electron beam model was modified to include the residual fields of the two copropagating CO₂ laser beams, which were used to excite the beatwave plasma wave. The recalculated results predicted that longitudinal bunching occurs with spacing related to the plasma wavelength. Also predicted is that after the beam exits from the plasma wave, it compresses down to a line focus at some distance past the center of the plasma wave, with focusing in the direction perpendicular to the plasma wave direction of propagation, and no focusing along the plasma wave direction. This suggests that the focusing may be due to the radial fields of the plasma wave. In this case, the effect of the plasma wave on the electron beam/laser beam combination is similar to focusing of a light beam by a cylindrical lens. These studies show that higher energy electron beams require higher amplitude plasma waves to be focused. Figure 5 shows the longitudinal bunching as

observed from above the beam and also focusing as observed from a side view of the beam. Figure 6 shows focusing near the minimum in a cross section view of the beam propagating out of the page, and also the variation of spot size versus plasma wave amplitude for electron beam energies from 5 keV to 50 keV (where zero spot size corresponds to the line focus). It is necessary for the electron beams used in these plasma wave diagnostics be characterized well, and we have started exploring using low power lasers, such as HeNe, injected across the electron beams as probes. Laser beam contour probes, for HeNe as well as CO₂, have been acquired for use with a concept experiment in our laboratory.

These results were included in the graduate student's Ph.D. dissertation, along with the results of extensive parameter studies (ref. 1). (Additional results obtained since the last renewal were presented at the listed conferences (refs. 2 -7).) Our next step was to input the parameters of these numerical experiments into a particle-in-cell package, for example VSIM, in order to corroborate these results (this effort is ongoing). The results obtained so far assume that the electron beam is very tenuous (very low current) and therefore there is no interaction between the electrons in the beam and between the electrons and the fields of the plasma wave and laser. The PIC code would include some of these interactions and would be a better predictor of the results of an experiment. A license for VSIM and a computer workstation having twelve cores were obtained for running the PIC codes during this past research period. Depending on the results of these additional numerical studies, an experiment could be performed in our small university laboratory, and if successful, scaled up to a larger wakefield plasma accelerator facility. In order to explore opportunities for future collaborations our research group has initiated contact with the ATF User Facility at Brookhaven National Lab and the FACET user facility personnel at SLAC in order to follow the development of their upgrades. We note that these simulation tools can be applied to study other examples of the interactions among electrons, positrons, protons, plasma waves, photon beams and radiation generation, applicable to accelerator science.

Our laboratory acquired a new large volume rectangular vacuum chamber within which optical components can be easily mounted to steer the laser beams, and on which several vacuum feed-throughs and detectors can be installed. (A patent disclosure

application has been submitted for the design of the large volume rectangular vacuum chamber.) Other additions to the laboratory include laser beam contour profile detectors, linear ccd cameras and additional pulse/delay generators, HeNe lasers, and gas jet valves. Also the workstation (12 core) and PIC code were acquired. With these additions to our university research program, this research group will be able to continue our studies of the interactions among electron beams, lasers and plasmas, and provide training for students, going forward.

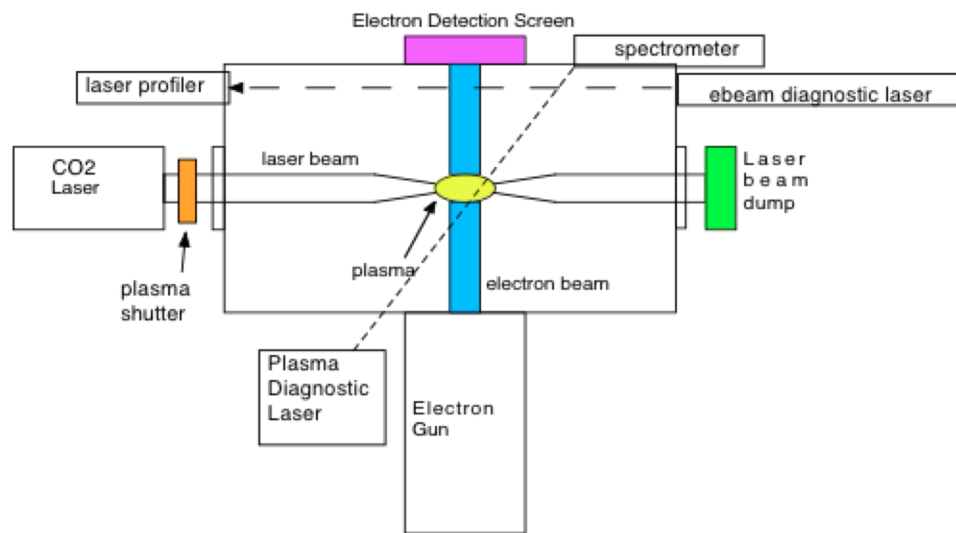


Figure 1. The numerical simulations parameters were based on the above proposed experimental set-up, in which a CO₂ laser is injected into a gas filled chamber (or gas jet) to produce a plasma wave, and the diagnostic 5-50 keV electron beam is injected perpendicular to the plasma wave. The diagram shows the new flexible, large-volume interaction vacuum chamber which replaced a smaller eight-way cross chamber.

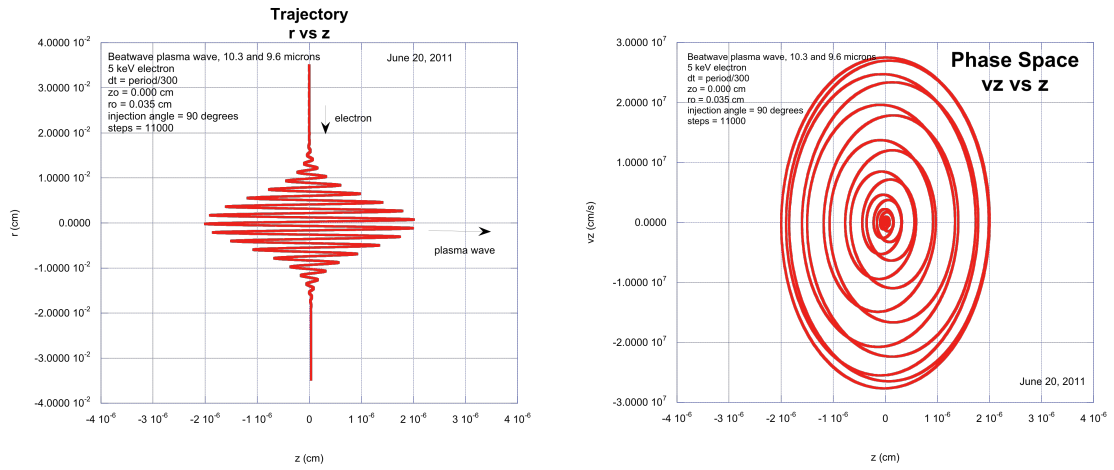


Figure 2. (left) Sample 2-D, single particle trajectories of a 5 keV electron propagating across the plasma wave and (right) the corresponding phase space diagram, v_z versus z .

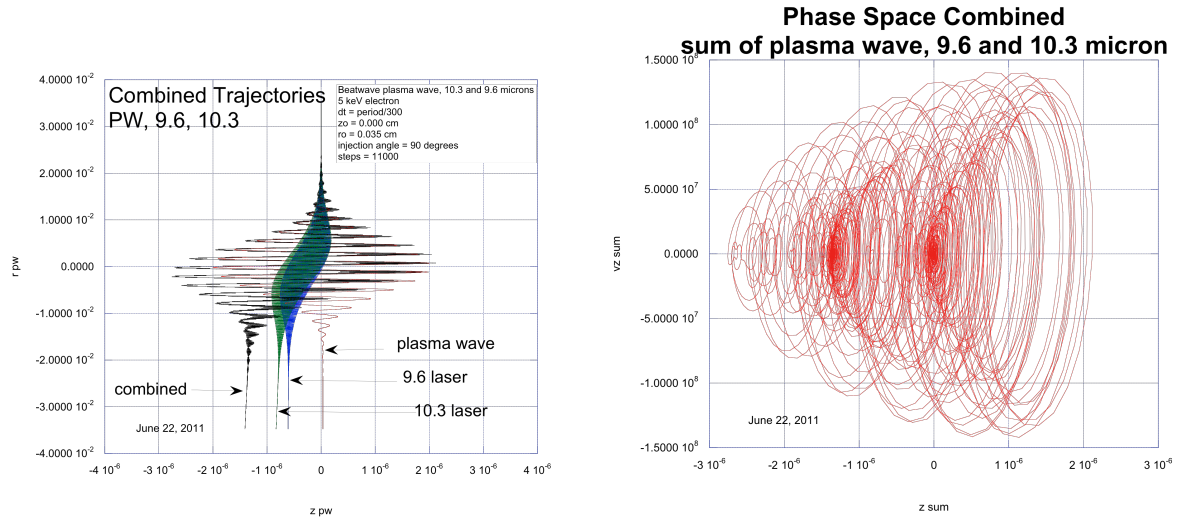


Figure 3. (left) Sample 2-D, single particle trajectories of a 5 keV electron propagating across the plasma wave, and the plasma wave is copropagating with two overlapping CO₂ laser beam wavelengths, and (right) the corresponding phase space diagram, v_z versus z .

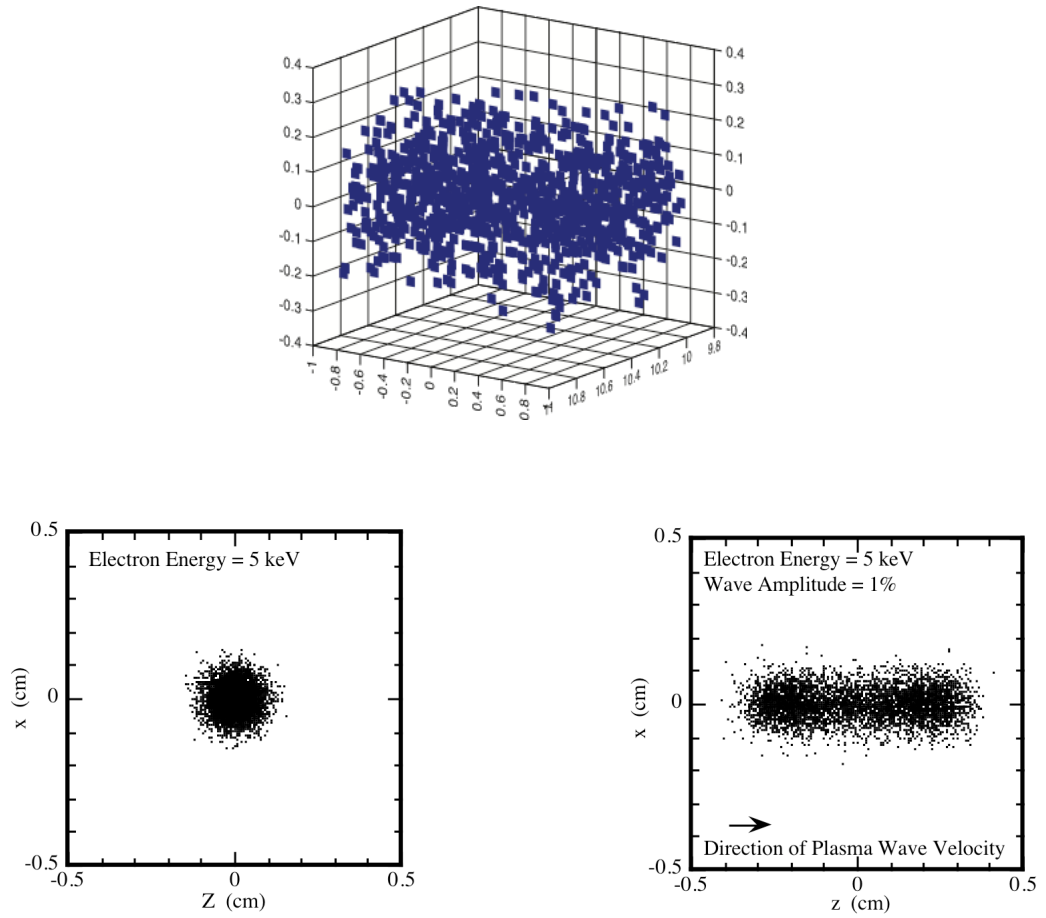


Figure 4: (top) Three Dimensional plot of the distribution of electrons in a beam propagating to the right. (left) Cross section plot of beam before it enters the plasma wave, and (right) Cross section plot of beam after it passes through the plasma wave, which shows spreading of the beam due to the plasma wave electrostatic fields.

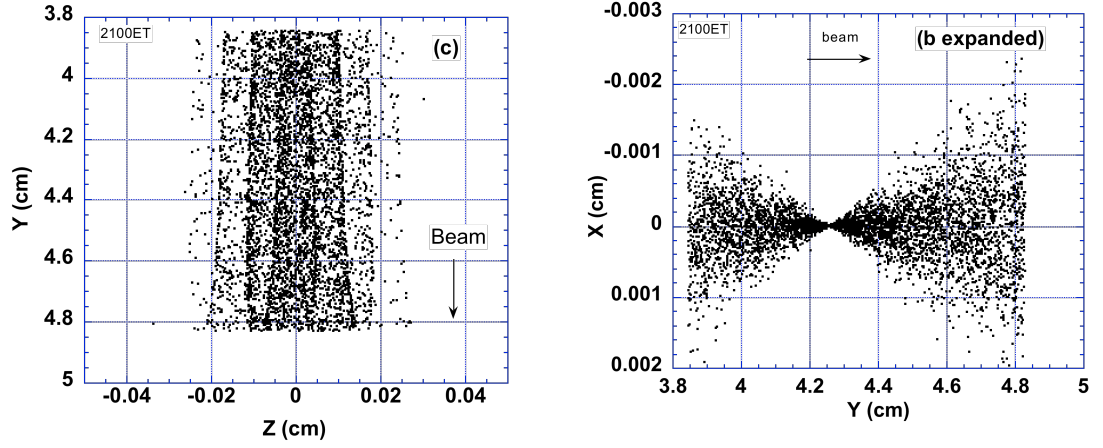


Figure 5. Examples of the interaction of a beam consisting of 5,000 electrons propagating across a combination of plasma wave and two laser beams. Bunching (left plot) along the length of the beam. Focusing (right plot) in the x-y plane shown above, but linear in the z plane (out of page).

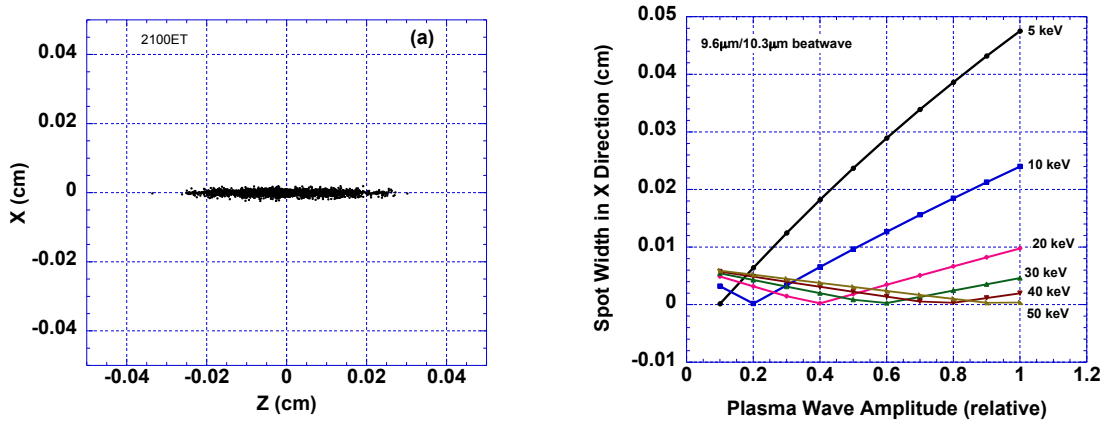


Figure 6. A plot showing the electron beam linear focusing in the x-y plane (Figure 5 (right)) for different energy electron beams as a function of the plasma wave amplitude.

5. List of Papers:

1. Arnesto Bowman, ““Electron Beam Dynamics in Plasma and Electromagnetic Waves Used in Plasma Wave Accelerator Studies”, Dissertation, Florida A. & M. University, 2013.

2. A. Bowman and R. L. Williams, “Electron Beam Focusing and Spreading due to Interactions with Copropagating Plasma Waves and Laser: Explanation of Simulation Results”, 58th Annual Meeting of the APS Division of Plasma Physics, San Jose, CA, October 31 – November 4, 2016. (BAPS 2016 DPP GP10.9)

3. A. L. Bowman and R. L. Williams, “Interactions of Plasma Waves and Lasers with Electron Beams Resulting in a Line Focus”, 57th Annual Meeting of the APS Division of Plasma Physics, Savannah, GA, Nov. 16-20, 2015.

4. Danielle Green and Ronald Williams, “Simulation of the Effects of Electric and Magnetic Fields on the Trajectory of an Electron”, presented at the 2015 Conference of the National Society of Black Physicists, Baltimore, MD, February 25, 2015

5. Ronald L. Williams and Arnesto L. Bowman, “Transverse Focusing of and Electron beam by Relativistic Plasma Waves and Laser Beams”, presented at the 451st International Conference on Plasma Science and the 20th International Conference on High Power Particle Beams, Washington, DC, May 25-29, 2014.

6. R. L. Williams and A. L. Bowman, “Diagnostic of Relativistic Plasma Waves Based on Transverse Injection of Energetic Electron Beams”, presented at the 20th Topical Conference on High-Temperature Plasma Diagnostics, Atlanta, GA, June 1-5, 2014.

7. Ronald Williams and Arnesto Bowman, “Charged Particle Diagnostics for Laser Excited Plasma Wave Accelerators”, presented at the IEEE Pulsed Power and Plasma Science Conference, San Francisco, CA, June 16-21, 2013.

6. The people who worked on this research activity, in addition to the P.I., are:

- a. Graduate Student, Arnesto Bowman, full support, and received the Ph.D. in Physics in 2013. Dissertation Title: “Electron Beam Dynamics in Plasma and Electromagnetic Waves Used in Plasma Wave Accelerator Studies”.
- b. Undergraduate student, Danielle Green, partial support to travel to a conference to present a poster on simulation of electron trajectories in electric field using various programming languages, which won best poster award.

