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Spatial and Temporal Dynamics of Relativistic Plasma Beat Waves

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Electrical Engineering

by

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DEDICATION

To my wife Rachna,

and my parents Ravi and Usha Lal.

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PUBLICATIONS

A.K. Lal et al., "Resonant Four Wave Mixing in Plasmas", paper presented at the 1990 American Physical Society, Division of Plasma Physics, Cincinnati, Ohio, November, 1990.

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ABSTRACT OF THE DISSERTATION

Spatial and Temporal Dynamics of Relativistic Plasma Beat Waves

by

Amit Kumar Lal

Doctor of Philosophy in Electrical Engineering

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Professor Chan Joshi, Chair

Recent experiments at UCLA have demonstrated that relativistic plasma waves, excited by two collinear electromagnetic waves beating at the plasma frequency, can be used to accelerate electrons to high energies. The accelerating electric field of this plasma beat wave is proportional to the plasma wave density modulation, n_1/n_o, and the total energy gain is proportional to this wave amplitude and the spatial length of the wave. In this dissertation, experimental results are presented of the accelerated electron energy spectrum, and of the properties of the plasma beat wave. In particular, the wave amplitude as a function of time, space, frequency, and wavenumber have been determined through Thomson scattering and forward scattering, In addition, Raman/Compton back scattering is developed as a diagnostic for both the plasma and the beat wave. Also, the heating of the plasma by the beat wave has been measured by monitoring the x-ray emission spectrum with a CCD camera used as a single photon counter.

Chapter 1

Introduction

Since the first electron accelerator was built in the 1930s, the maximum electron energies have increased from 1 MeV up to 50 GeV. The maximum acceleration gradient in conventional accelerators, however, is limited to 10-100 MeV/m, due to RF breakdown in the walls of the structure. Therefore, achieving higher electron energies requires larger and more expensive accelerators.

One method to overcome this limit of the acceleration gradient is to use a plasma as the accelerating structure. Since the plasma is already broken down, it can sustain much higher electromagnetic fields than conventional RF accelerators. In 1979, Tajima and Dawson[1] proposed several schemes to accelerate particles from the longitudinal electric fields of relativistic plasma waves driven by intense laser beams. One particular scheme, the plasma beat wave accelerator (PBWA), utilizes two co-propagating laser beams such that the frequency difference of the lasers matches the natural frequency ω_p of the plasma. Several groups around the world have reported the generation of plasma beat waves [2, 3, 4, 5], as well as successful electron acceleration [6, 7, 8].

This thesis describes the latest developments in the PBWA experiments carried out at UCLA under the supervision of Professor Chan Joshi. In particular, several experiments are discussed that characterize the details of the electron acceleration and plasma wave dynamics. Chapter 1 begins with an introduction to relativistic plasma beat waves and the experimental setup. Chapter 2 describes the successful acceleration of injected electrons up to 30 MeV, and the measurement of the accelerated electron energy spectrum. A single shot, eight channel spectrometer, has been developed and implemented.

In Chapter 3, Thomson scattering is used as a diagnostic for the relativistic plasma beat waves responsible for electron acceleration. Thomson scattering is used to determine the plasma beat wave amplitude as a function of time, frequency, space, and wavenumber. When the plasma wave amplitude and phase are known as a function of time and space, the expected energy gain of an injected electron can be estimated. In Chapter 4, time and frequency resolved forward scattering is used as a second independent diagnostic of the plasma wave amplitude and length. The intensity of the forward scattered light shifted in frequency by ω_p is proportional to $(\int n_1/n_o dl)^2$, where n_1/n_o is the plasma wave amplitude per unit length dl. Chapter 5 discusses the data from experiments on the back scattered light from the plasma. The back scatter gives direct information about non-relativistic plasma waves, such as those produced from Stimulated Raman and Brillouin Scattering, and indirect information about the plasma beat wave since coupling between the 'fast' (relativistic) and 'slow' (non-relativistic) waves will appear in the back scatter. It has been shown previously[9] that the presence of a large amplitude plasma wave results in the heating of the plasma electrons.

In Chapter 6, this heating is measured by monitoring the x-ray radiation spectrum from the plasma. Chapter 7 summarizes the results of the current UCLA experiments, and discusses the implications on future PBWA work.

This thesis describes the continuation of the work carried out by the present author that builds on the previous work of other students. The reader should refer in particular to Ph.D. theses by W.P. Leemans[10] "Topics in High Intensity Laser-Plasma Interactions" (UCLA, 1991) and M.J. Everett[9] "The Physics of Beat-Excited Plasmas" (UCLA, 1994) for completeness.

1.1 Plasma Beat Waves

In the plasma beat wave accelerator (PBWA), two electromagnetic waves (ω_0, k_0) and (ω_1, k_1) excite an electrostatic plasma wave (ω_2, k_2) that obeys the relations[11]

$$\omega_2 = \omega_0 - \omega_1, \qquad k_2 = k_0 - k_1, \tag{1.1}$$

where the plasma density n_o has been chosen so that ω_2 equals the plasma frequency $\omega_p = 4\pi n_o e^2/m$. Here e is the electron charge, and m is the electron mass. The phase velocity of the plasma wave is equal to the group velocity of the light waves in the limit $\omega_{0,1} \gg \omega_p$. This ensures that the particles trapped in the plasma wave will travel in near synchronism with the light pulses. For the UCLA PBWA experiments, the laser frequencies are $\omega_o = 2\pi c/10.6\mu m = 1.78 \times 10^{14}$ s^{-1} and $\omega_1 = 2\pi c/10.3\mu m = 1.83 \times 10^{14}$ s^{-1} while $\omega_p \sim 10^{12}$ s^{-1}, so this requirement is satisfied.

In Lagrangian coordinates, the evolution of the plasma wave can be modeled by the 1-D differential equation[12]

$$\frac{d}{dt}\left(\gamma\frac{d\xi}{dt}\right)+\omega_p^2\xi=\alpha_1\alpha_2\frac{c^2\Delta k}{2}sin(\Delta\omega-\Delta kx) \tag{1.2}$$

Here ξ is the electron displacement, $\alpha_{1,2}=eE_{1,2}/m\omega_{1,2}c$ are the normalized laser intensities, $\Delta\omega$ is the laser difference frequency, Δk is the laser wavenumber difference, and the damping of the wave (which is on the timescale of its saturation) has been neglected. A solution of this equation is shown in Figure 1.1, for $\alpha_1 = 0.17$, $\alpha_2 = 0.07$ (150 ps risetime, 300 ps FWHM), and assuming the initial density is 10% above the theoretical resonant density (where ω_p equals $\omega_o - \omega_1$), with the density decreasing at the experimentally measured rate of 20% per 100 ps. (Section 3.2). The initial density must be set ~10% above the resonant den-

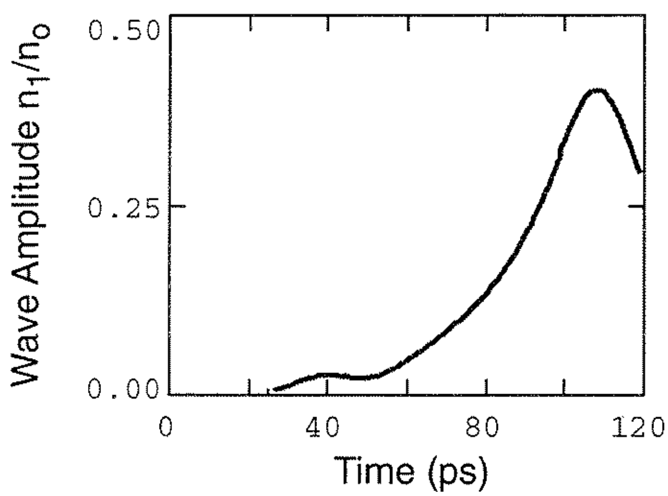


Figure 1.1: Solution to Equation 1.2 for the following parameters: $\alpha_1 = 0.17$, $\alpha_2 = 0.07$, n_{init}=1.1 n_{res}

sity to compensate for hydrodynamic expansion of the plasma and any plasma blowout induced by the laser[13] or the plasma wave[14].

This predicts a wave reaching a peak amplitude of approximately 35%, and reaching this peak before that of the laser pulses. This equation, which applies to one point in space, can be applied to all points along the laser axis, treating each point independently, but with a slightly different laser and density evolution due to the laser propagation[7] (See Figure 1.2). For example, one Rayleigh length z_o

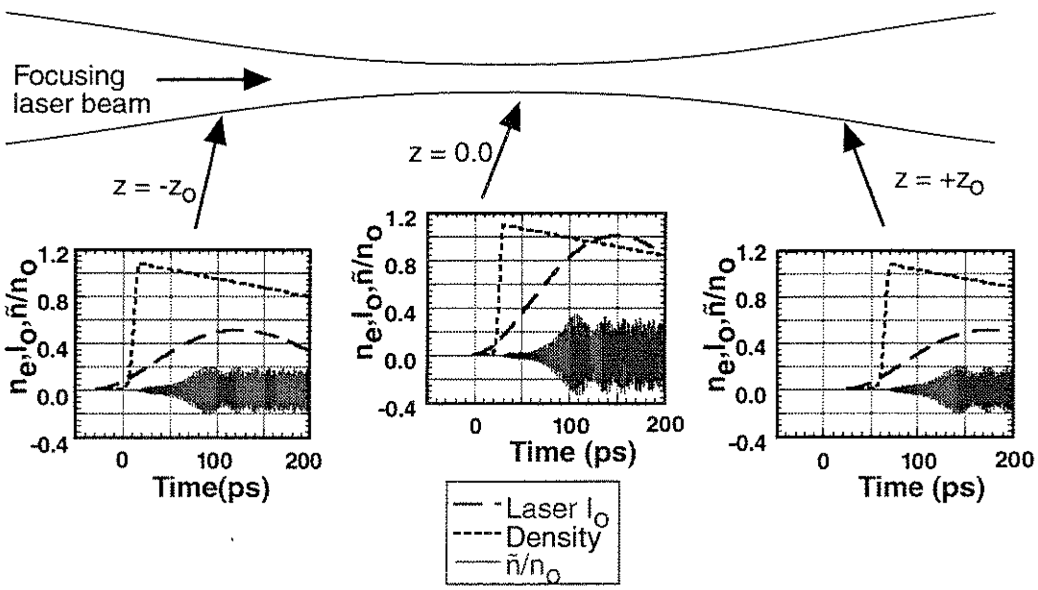


Figure 1.2: 1-D Model to Predict Wave Amplitude vs. Space.

before the best focus of the laser, the peak laser intensity is reduced by a factor of two, and the laser arrives about 30 ps earlier than it does at best focus. The plasma formation and the beat wave evolution are determined from this laser profile. A similar situation can be seen one Rayleigh length after best focus, except that the events are occuring about 60 ps later. It is important to note that although the wave amplitude in Figure 1.2 remains high for the duration of the laser pulse (since there is no damping included), the phase coherence of the wave is lost after the first saturation. Also, ion effects, which were not included here, become important after a few ion plasma periods ($\nu_{pi} \approx 50$ ps). Therefore, only the data in approximately the first 100 ps is an accurate representation of the beat wave evolution.

From this model, one can construct the wave amplitude as a function of space and time, as shown in Figure 1.3. Early in time (t = 60 ps), the wave has not

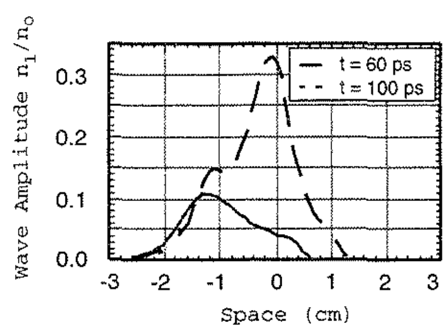


Figure 1.3: Wave Amplitude vs. Space at t=60 and t=100, based on the 1-D Model.

reached the best focus yet, and has a smaller amplitude due to the reduced laser intensity. At t = 100 ps, the maximum wave amplitude has been reached, and extends for ~1 cm in space (FWHM).

1.2 Experimental Setup

The experiment consists of five main components (See Figure 1.4) : a) CO_2 Laser, b) Plasma, c) Electron Beam, d) Electron diagnostics, and e) Optical diagnostics.

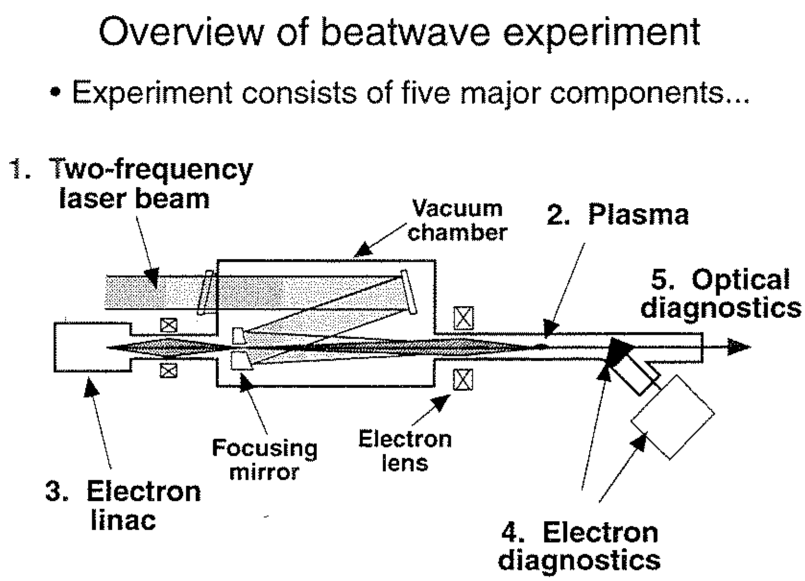
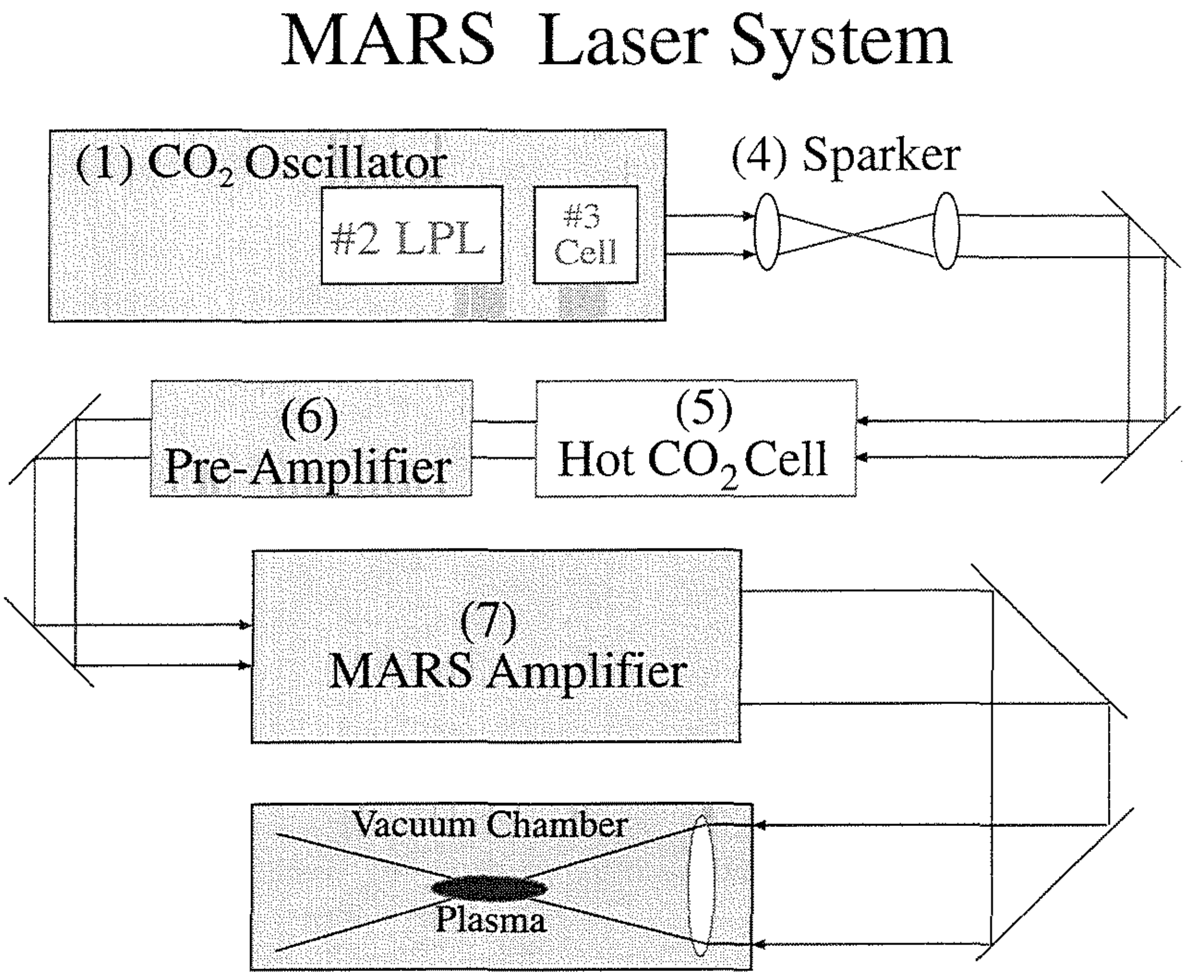


Figure 1.4: Overview of Experimental Setup

1.2.1 Laser

The CO_2 laser system (discussed in more detail in Appendix I) is designed to produce a two frequency laser beam (10.6, 10.3 μm) with an energy of $\sim$ 100J and a pulse width of $\sim$ 300 ps (FWHM). The laser system begins with a hybrid CO_2 oscillator (See Figure 1.5). The high pressure oscillator (Lumonics 280, 1.5 ATM) produces a multimode pulse with an energy of approximately 200 mJ and a pulsewidth of 150 ns (FWHM). The oscillator cavity is seeded by a low pressure laser (22 Torr) to produce a single longitudinal mode. Also within the main cavity is a small gas cell which can be filled by various absorber gases (SF_6, Freon 115, etc) to adjust the gain of the various laser lines (10.6 μm, 10.3 μm, and 9.6 μm). By adjusting the gas cell mixture and by tuning the cavity length with a small piezoelectric crystal, it is possible to produce approximately equal output on a pair of CO_2 lines (10.6 and 10.3 μm, for example).



(1) - Oscillator : 150 mJ, 200 ns, λ = 10.6 μm, multi-mode pulse
(2) - Low Pressure Laser : selects a single longitudinal mode
(3) - Absorber Cell : used for two frequency laser operation
(4) - Sparker : creates fast cutoff (< 50 ps) of pulse
(5) - Hot CO_2 Cell : transmits only a short pulse (75 μJ, 100 ps)
(6) - Pre-Amplifier : amplifies to 1 mJ, some pulse broadening
(7) - MARS Amplifier : produces 150 ps rise, 300 ps FWHM pulse

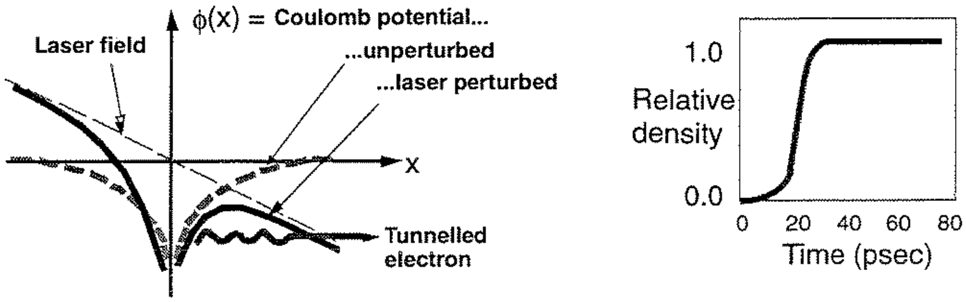
10.6μm : 60J ($v_{osc}/c = 0.17$), 10.3 μm : 20J ($v_{osc}/c = 0.10$)
Spot Radius : 150 μm, Rayleigh Range $2z_o = 1.3$ cm

Figure 1.5: Schematic of the MARS Laser System

This long (150 ns), single longitudinal mode pulse is focused through a spark gap, which is triggered at the peak of the laser pulse. When the spark gap fires, the strong fields of the laser quickly produce a plasma, which reflects the remainder of the laser pulse. The result is a pulse with a very rapid ($\approx$ 50 ps) cutoff. The chopped pulse then triple passes a three meter cell containing 35 mT of CO_2 gas at 400 °C. Through the process known as free induction decay (described in Appendix I), the 100 ns pulse is converted to a 100 ps pulse with approximately the same peak power. The pulse then double passes a 1 ATM TEA pre-amplifier (Lumonics 103), which increases the energy by a factor of 10-20, and also gain broadens the pulsewidth to approximately 250 ps. The pulse then triple passes the main MARS amplifier (2.3 ATM), which amplifies the pulse up to 100 Joules with a FWHM of 350 ps. This pulse then enters the vacuum chamber through a 8" NaCl window and is focused by a f/11.5 parabolic mirror to a near diffraction limited 300 μm spot diameter at the center of the vacuum chamber. This results in a peak laser intensity of 5×10^{14} W/cm^2, or a normalized quiver velocity $\alpha = eE/m\omega c = 0.2$.

1.2.2 Plasma

The plasma is produced by the laser itself by tunneling ionization[15] of a static fill of hydrogen gas (140 mTorr). Tunneling ionization occurs when the strong electric fields of the laser suppress the atom's Coulomb potential barrier, and allow the electron to tunnel free (See Figure 1.6). The evolution of the plasma density $n(t)$ as a function of time can be determined from the following rate



Plasma Parameters : Gas : Hydrogen
Density : 8.6×10^{15} cm^{-3}
Plasma Period : 1.2 ps
Plasma Wavelength : 360 μm
Lorentz Factor : 34

Figure 1.6: Plasma Production by Tunneling Ionization.

equations :

$$\frac{dn(t)}{dt} = w(t)(n_0 - n(t)) \tag{1.3}$$

$$w(t) = \frac{4me^4}{\hbar^3}\left(\frac{E_i}{E_h}\right)\zeta \exp\left[\frac{-2}{3}\left(\frac{E_i}{E_h}\right)^{3/2}\zeta\right], \tag{1.4}$$

where n_0 is the initial neutral gas density, $\zeta = E_a/E(t)$, $E_a = 5.21 \times 10^{11}$ V/m is the atomic unit of electric field, E(t) is the applied electric field, E_i is the ionization potential of the atom, and E_h is the ionization potential of hydrogen. For our laser parameters, assuming atomic rather molecular hydrogen, the plasma is fully ionized within the first 20-30 ps of the laser pulse. From tunneling ionization theory, the plasma has a transverse temperature of approximately 75 eV, and a longitudinal temperature of a few eV [16, 17].