Measurements of the Beatwave Dynamics in Time and Space*

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Abstract

We report on continuing experiments on the Plasma Beat Wave Accelerator, which uses an intense two-frequency CO_2 laser pulse to resonantly drive a large amplitude, relativistically-propagating electron plasma wave suitable for electron acceleration. Previously, energy gains of a factor 15 (from 2 MeV to 30 MeV) have been obtained [1]. Also, collective scattering of a probe laser beam has allowed us to measure $\tilde{n}(\omega,k)$ and $\tilde{n}(\omega_m,t)$ where m=1,2 are the fundamental and harmonic of the large amplitude plasma wave. This powerful Thomson scattering technique has now been extended to measure $\tilde{n}(z,t)$, where z is the coordinate along the CO_2 propagation direction. Nonlinear dynamics such as relativistic detuning and ponderomotive effects can complicate the longitudinal amplitude profile and coherence. Experimental results show a plasma wave with a peak amplitude of approximately 35%, with a FWHM of 100 ps, and extending for 1 cm in space. These wave parameters are consistent with the observed energy gains of accelerated electrons.

I. INTRODUCTION

In plasma based accelerator schemes, a relativistically propagating (γ_{ph} » 1) plasma wave is used for accelerating charged particles. Since the accelerating field is directly related to the plasma wave amplitude, it is important to know both the spatial and temporal structure of the wave in order to predict the energy gain or loss of a particle. In the Plasma Beat Wave Accelerator, a relativistic plasma wave (RPW) is resonantly excited by two laser beams in a tunnel ionized plasma such that the frequency difference of the lasers $\Delta\omega = \omega_0 - \omega_1$ is approximately equal to the plasma frequency ω_p. The spatial and temporal structure of the RPW depends on many factors, including the laser pulseshape and profile, the plasma ionization and expansion times, and the transverse ponderomotive forces of the laser and of the plasma wave itself. The features of the plasma wave are diagnosed with frequency and wavenumber resolved Thomson scattering.

II. EXPERIMENTAL SETUP

In the experiment, the plasma wave is generated by the ponderomotive force exerted on the plasma electrons by beating two frequencies in a short (150 ps rise, 300 ps FWHM) CO_2 laser pulse. The laser also creates the plasma by fully ionizing hydrogen gas via tunneling ionization, typically in the first 20-30 psec. The hydrogen gas pressure is adjusted so that the resonant plasma frequency matches the frequency difference of the two laser lines ($\lambda = 10.6$ μm and 10.3 μm). The initial density must be set about 10-15% higher than the resonant density (=9.4 x 10^{15} cm^{-3}) to compensate for plasma blowout induced by the laser [2].

The plasma density fluctuations associated with the RPW are measured using collective Thomson scattering by a 2 ns (FWHM), 50 MW, 0.53 μm optical probe beam incident on the plasma at an angle of 87^o relative to the CO_2 laser axis. Both the frequency and wavenumber of the waves in the plasma can be determined as a function of time by this diagnostic, since the ω and k of the scattered light is shifted by the plasma waves.

The driven RPW has a wavenumber that is determined by the wavenumber difference of the two laser lines at $\Delta k = k_0 - k_1 = 1.83 \times 10^{-2}$ μm^{-1}. Due to this small k, a line focus of the probe beam is required to resolve the k spectrum. The experimental setup is shown in Figure 1. The input lenses bring the probe beam to a line focus of length 6 mm and height 100 μm at the plasma. The output lenses eliminate the astigmatism in the beam and refocus the unscattered light on a razor blade beam dump. The angular shift of the scattered light, $\Delta k/k_{pr}$, is 1.48 mrad, which corresponds to a shift of 1.05 mm per RPW harmonic at the razor blade. The razor blade blocks the main beam, but allows the scattered light to pass.

After the razor blade beam dump, the optical system has two possible configurations. In the first method, the plane of the razor blade (k space) is imaged onto the entrance slit of an imaging spectrometer, with each harmonic separated vertically by 190 μm. The spectrometer disperses the harmonics in frequency on the axis perpendicular to the k dispersion. The output of the spectrometer is then sent to a streak camera, which

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disperses the signal in time to give ñ(ω_m,t). If the streak camera is operated on a slow sweep speed, the output is ñ(ω,k), a snapshot of the ω-k space [1].

In the second configuration, an additional cylindrical lens is used to re-image the scattered light from the plane of the plasma onto the slit of the spectrometer. The spectrometer then disperses the light in frequency, which gives the amplitude as a function of space and frequency, ñ(z,ω). Also, the spectrometer can be used to select a single frequency, and the amplitude of this frequency as a function of time and space, ñ(z,t), can also be seen.

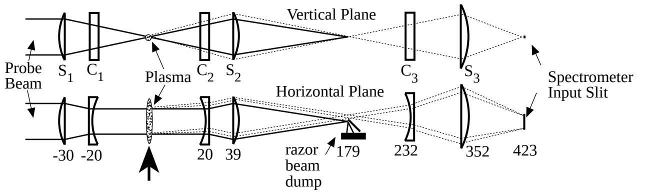

Figure 1: Thomson scattering setup. Numbers below lenses are the position relative to the plasma in centimeters. The letters S and C stand for spherical and cylindrical respectively, and the focal lengths are S1=S2=30 cm, C1=C2=-20 cm, S3=50 cm, and C3=-50 cm. The probe goes from left to right, coming to a line focus at the plasma, and then the scattered light is imaged onto a spectrometer followed by a streak camera. Lens C3 has been added for the spatial Thomson scattering

III. EXPERIMENTAL RESULTS

A. Time Resolved Thomson Scattering

Figure 2 shows a streak of the plasma wave amplitude, with frequency on the vertical axis, and time moving to the right. The scattered light shows a clear signal with a frequency shift of ω_p, and also a signal shifted by $2\omega_p$. The downward shift in frequency of the fundamental and 2nd harmonic of approximately 10% over 100ps is too large to be explained by relativistic frequency detuning, and thus strongly suggests a decrease in plasma density due to blowout of the plasma.

There are two ways to compute the plasma wave amplitude from this experimental data. First, the wave amplitude is directly proportional to the ratio of scattered power in the first harmonic to the power in the incident probe beam. Second, the ratio of power in the 2nd harmonic to the power in the fundamental is also proportional to the amplitude of the fundamental. Both of these methods show a peak wave amplitude of about 35% with a duration of about 100 ps. Simulations show that the peak wave amplitude is limited by ponderomotive blowout of the plasma due to the beat wave itself [3].

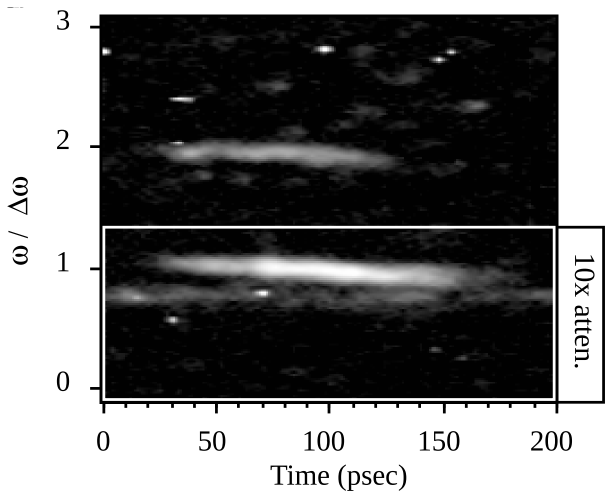

Figure 2 : Time resolved spectrum of Thomson scattered light from the fundamental and 2nd harmonic of the beat wave. Stray light at 0.8 Δω and the beat wave fundamental are attenuated by a factor 10.

B. Space Resolved Thomson Scattering

The experimental data in Figure 2 shows the plasma wave amplitude averaged over the 6 mm length of the probe beam. However, the energy gain of a particle is determined by the $\int E_{ac} \cdot dl$ seen by the particle, where $E_{ac} = \varepsilon\sqrt{n_e}$ is the accelerating field, ε is the wave amplitude, and n_e is the plasma density Therefore, it is important to know the wave amplitude along the particle's axis of propagation. A numerical solution of the wave amplitude differential equation shows the FWHM of the wave to extend for approximately 1 cm [4]. To determine this experimentally, the probe beam was expanded to 1.2 cm, and then the scattered light from this line focus was imaged onto the spectrometer. To see the wave amplitude vs. space and frequency, the streak camera was operated at a slow sweep speed (2 ns/mm), so the image had no time resolution. A lineout of the scattered light shifted by a frequency of ω = (1 ± 0.1) Δω is shown in Figure 3(a), and extends for approximately 1 cm.

In order to see the wave amplitude vs. space and time, the streak camera had to be rotated 90°, so space and time would be on opposite axes. Figure 3(b) shows a typical streak, where the spectrometer has been set to only pass light shifted by Δω. This streak shows a plasma wave extending for approximately 8 mm. In addition, a lineout through the center shows a rise time of approximately 60 ps, and a much faster fall time. This is consistent with the

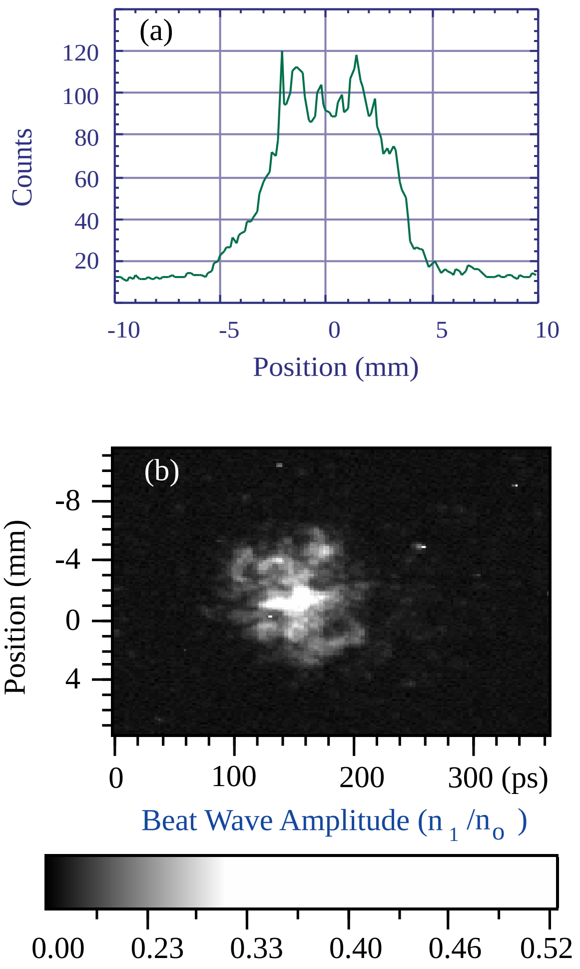

Figure 3 : (a) Line out of the scattered power at a frequency shift of Δω, as a function of space. The wave extends for approximately 8 mm. (b) Streak image of the scattered light shifted by Δω, with space on the vertical axis, and time moving to the right. Near best focus of the CO_2 laser, the beat wave reaches a peak amplitude of 40%.

simulations, which show the wave growing linearly with the laser intensity, and then crashing near the peak due to rapid plasma blowout [3]. Also, the streak shows the wave amplitude to be peaked near the best focus of the CO_2 laser, and to be smaller in the areas where the laser intensity is lower. The spatial resolution of the system is approximately 1 mm. The fine structure in the scattered light may be due to x-ray noise and statistical variations in the number of photoelectrons in the streak camera.

The expected energy gain of a electron in a plasma wave can be estimated by integrating the product of the accelerating field and the length of the wave. For example, a wave with amplitude of 30% for 1 cm at a density of 9.4 x 10^{15} cm^{-3} would produce an energy gain of approximately 28 MeV. From the experimental streaks, it is possible to numerically integrate the wave amplitude along the laser axis, and compare this with the measured experimental electron energies from an electron energy spectrometer.

The calculated maximum energies from the streak data (assuming perfect phasing of the electrons and the plasma wave over its full length) agree well with the energy spectrometer. For example, on shots where the energy spectrometer showed electrons up to 25 MeV, the Thomson scattering showed peak wave amplitudes of up to 40%, with a spatial FWHM of about 8 mm. Similarly, when the Thomson scattering only showed wave amplitudes of 10% (due to shot-to-shot variations in the laser intensity), the highest electron energies seen on the spectrometer were around 5 MeV.

IV. CONCLUSIONS

The relativistic plasma waves generated in the Plasma Beat Wave Accelerator have been extensively studied with collective Thomson scattering. The plasma wave amplitude has been studied as a function of several parameters, including frequency, time, space, and wavenumber. Experimental results show a plasma wave with a peak amplitude of approximately 35%, with a FWHM of 100 ps, and extending for 1 cm in space. These wave parameters are confirmed by the observation of accelerated electrons, in which the energy gains are consistent with the $\int E_{ac} \cdot dl$ of the plasma wave.

V. REFERENCES

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