FIRST OBSERVATIONS OF ACCELERATION OF INJECTED ELECTRONS IN A LASER PLASMA BEATWAVE EXPERIMENT

N.A. Ebrahim*, F. Martin, P. Bordeur, E.A. Heighway**, J.P. Matte, H. Pepin and P. Lavigne
INRS-Energie, Varennes, Quebec, Canada J0L 2P0

Abstract

We report the first experimental observations of acceleration of injected electrons in a laser driven plasma beatwave. The plasma waves were excited in an ionized gas jet, using a short pulse high intensity CO_2 laser with two collinearly propagating beams (at λ = 9.6 μm and 10.6 μm) to excite a fast wave ($v_p \approx c$). The source of electrons was a laser plasma produced on an aluminum slab target by a third, synchronized CO_2 laser beam. A double-focusing dipole magnet was used to energy select and inject electrons into the beatwave, and a second magnetic spectrograph was used to analyze the accelerated electrons. Electron acceleration was only observed when the appropriate resonant plasma density was produced ($\approx 10^{17}$ cm^{-3}), the two laser lines were incident on the plasma, and electrons were injected into this plasma from an external source.

Introduction

The laser plasma beatwave accelerator was first discussed by Tajima and Dawson, in the context of an ultra-high energy particle accelerator[1]. The physical mechanism underlying this scheme is the optical mixing of laser light in an underdense plasma[2], which excites an electron plasma wave as a result of the beat pondermotive force. The potential troughs associated with the longitudinal plasma wave can trap sufficiently energetic electrons injected from an external source and accelerate them to relativistic energies. Theoretically at least, accelerating gradients of order $\sqrt{n_e}$ V/cm seem possible, where n_e is the plasma density in units of cm^{-3}.

A study of the plasma beatwave concept involves a study of three basic problems: that of producing a source of underdense plasma of an appropriate size and density; that of generating a plasma wave with laser beams and understanding the mechanisms of amplitude growth, saturation and decay of this wave, as well as its effect in modifying the plasma density; and finally that of injecting electrons into such a system, trapping the electrons and accelerating them to relativistic energy. The first of these problems has been investigated extensively over the past two decades in the field of plasma physics. Plasma sources suitable for a study of the beatwave concept are arc discharge plasmas, exploding submicron foils, pinch discharges (both 'Z' and 'θ' pinches) and gas jet plasmas. The second problem has been studied both analytically[2,3,4] and in computer simulations in numerous studies[1,5]. There have also been recent experiments to identify and establish the existence of large amplitude plasma waves as a result of the optical mixing of laser light[6]. The problem of particle trapping and acceleration has also been studied quite extensively in computer simulations[1,5] over the past two decades, since wave-particle interaction is a problem of general interest in plasma physics. However there have not been direct experimental studies to verify important aspects of the theoretical predictions.

* Atomic Energy of Canada Limited
Chalk River Nuclear Laboratories
Chalk River, Ontario, Canada K0J 1J0

** Now at Los Alamos National Laboratory
Los Alamos, New Mexico, USA 87545

This paper discusses a novel experimental approach to test the laser plasma beatwave accelerator concept. In this approach, the three main elements of the beatwave concept discussed above (i.e., the plasma source, electron plasma wave and the injection electron source) are all driven by a single, short pulse CO_2 laser operating at two frequencies. This greatly reduces the complexities of such an experiment by reducing the generally difficult problem of synchronization of a short laser pulse, a rapidly varying plasma density and a short burst of injection electrons, to a simple problem of setting up appropriate optical delays between the various laser beams emanating from a single laser. Nevertheless, this approach gives us a great deal of flexibility to conduct a wide range of experiments necessary to study the generation and dynamics of the beat plasma wave as well as the important problem of wave-particle interaction in a high phase-velocity electron plasma wave. Indeed as we point out later, a simple extension of our present approach may well have important implications for a configuration which would be appropriate for the test of a multistage beatwave concept as well.

Experiments and Results

Laser Facility

The experiments were performed with a high intensity CO_2 laser system shown schematically in Fig. 1. This system can be operated in a single frequency [10 P(20)] or dual frequency [9 P(20), 10 P(16)] mode. In the single frequency operation, the laser chain amplifies the 10 P(20) line at 944.2 cm^{-1} (λ = 10.6 μm) to produce a 1.0 ns FWHM pulse containing 75 Joules maximum. For the dual wavelength experiments, the laser chain was used to amplify the 9 P(20) line at 1046.8 cm^{-1} (λ = 9.55 μm) and the 10 P(16) line at 947.74 cm^{-1} (λ = 10.55 μm) to yield 30 Joules maximum in each of the two wavelengths. Since these lines have similar small signal gains, a good control of the relative energy at each frequency could be maintained. The use of reflective focusing optics and parallel windows all along the laser chain ensures good beam collinearity for the two wavelengths. The P- polarized light beam (main beam in Fig. 1) was focused at near normal incidence by an f/6, 60 cm focal length parabola. At best focus, 50% of the energy was contained within a 120 μm diameter focal spot. Only those shots for which the synchronization between the pulses at each frequency was better than 100 ps as measured on a 1 GHz oscilloscope, were retained for analysis.

Plasma Source

When two travelling electromagnetic waves, (ω_0, k_0) at 9.6 μm and (ω_1, k_1) at 10.6 μm, are injected into an underdense plasma, the beat of the two waves gives rise to a non-linear pondermotive force $\nabla \langle E^2 \rangle$ which excites plasma oscillations at the frequency ω_p and wavenumber k_p which satisfy the usual frequency and wavenumber matching conditions $\omega_p = \omega_0 - \omega_1$ and $k_p = k_0 - k_1$. For the two wavelengths used in these experiments this resonance condition occurs at a plasma density of 10^{17} cm^{-3} giving the phase velocity of the plasma wave $v_p = \omega_p/k_p = c(1-\omega_{pe}{}^2/\omega_0{}^2)^{1/2}$ = 0.995 c. Although a resonant density of 10^{17} cm^{-3} can be attained in an arc or pinch discharge, we have used the much simpler technique of laser breakdown of a low pressure gas, as this technique has several desirable features. Since breakdown of the gas is limited to a high laser intensity region in the focal volume, where the beat plasma wave is excited as well, it is not necessary to transport the laser beam through a significant region of the plasma. The initial gas filling pressure and the laser intensity are adjusted so that the resonant density is reached near the peak of the laser pulse, in order to obtain the maximum saturated amplitude of the plasma wave in a time scale short enough to avoid the deleterious effects due to the ion motion.

The plasma density and the density profile were measured with a Mach-Zehnder interferometer using part of the main CO_2 laser beam ($\approx$ 4%) as a probe beam, after the necessary spatial filtering (see Fig. 1, inset). The plasma was imaged with an afocal telescope, with a magnification of two and recorded by burning a Polaroid (TM) film. Since the probe pulse has a duration of 1.0 ns we cannot obtain any temporal resolution of the ionization phase where the electron density increases very rapidly. Consequently we have obtained interferograms at 2.0 ns and 5.0 ns after the plasma producing CO_2 laser pulse for static pressures of 0.3 Torr < p < 2.0 Torr of dry air. Since recombination and particle diffusion are negligible on this time scale, interferometry gives the peak electron density. The Abel inverted electron density profile (Fig. 2) shows the plasma to be cylindrical with a diameter of 2.0 mm FWHM. The laser beam has a focal diameter of 0.12 mm and a depth of focus of 1.5 mm. The dependence of the average value of the electron density in the focal volume, on the filling pressure for a probe delay of 2.0 ns is shown in Fig. 3. For comparison, the solid line gives the electron density corresponding to fully stripped nitrogen. In Fig. 3, an electron density of 10^{17} cm^{-3} is obtained for a filling pressure of 0.5 Torr with a degree of ionization Z $\approx$ 3. For a filling pressure of greater than 1.0 Torr the gas molecules are fully stripped. In this pressure range, the average value of the electron density is not very sensitive to laser energy. The plasma dimension is also approximately independent of the filling pressure.

Observations of Electromagnetic Sidebands

Measurements of electromagnetic sidebands for dual wavelength illumination provide further evidence that resonant plasma density has been attained in a given laser shot. The upshifted (anti-Stokes) and downshifted (Stokes) sidebands are produced when the low and high frequency pump parametrically couple to the beat plasma wave ($\omega_9 + \omega_p$ and $\omega_{10}-\omega_p$ respectively). For laser intensities above threshold, this could be due to the stimulated forward Raman scattering, whereas for the lower laser intensities it could be due to Thomson scattering. In either case, the sidebands are forward propagating. However, in our experiments the intensity of the unfocused laser beam is sufficient to generate a relatively strong anti-Stokes sideband signal in air along the path between the laser and the vacuum chamber, thus precluding any measurements in the forward direction. We have therefore made measurements of the anti-Stokes sideband signal in the backscatter direction, since the backscatter signal cannot originate from reflected laser light because of the low plasma reflectivity. The generation mechanism of the anti-Stokes sideband (Fig. 4) is as follows. A low frequency (<< ω_p) long wavenumber ($\approx$ 2 k_9) ion acoustic wave generated by stimulated Brillouin scattering of the 9.6 µm pump, parametrically couples to a high frequency (ω_p) short wavenumber ($k_p = k_0-k_1$) beat plasma wave to produce another forward propagating plasma wave with a frequency (ω_p) and wavenumber ($2k_9+k_p$). The 9.6 µm radiation can now either Raman scatter or Thomson scatter off this plasma wave to produce the backscattered radiation at 8.7 µm. Although this is an indirect process, in that the forward propagating plasma wave is driven by the two laser byproducts (beat plasma wave and ion acoustic wave) we believe the backscattered signal provides a relative measure of the amplitude of the beat plasma wave.

Figure 5 shows the amplitude of the backscattered 8.7 µm radiation normalized to the backscattered 9.6 µm signal as a function of the initial gas filling pressure for a laser intensity of 2 x 10^{14} W/cm^2. The curve is rather broad, with a peak in the pressure range 0.4-0.5 Torr which is consistent with the interferometry measurements which show an average density of 1 x 10^{17} cm^{-3} in this pressure range. The rather broad nature of the curve is due to the dynamics of the ionization process, which has been modeled theoretically. Essentially, at low filling pressures, the resonant density is reached late in the laser pulse, where the low laser intensity cannot drive the beat plasma wave to a large amplitude (resulting in low backscatter). At high filling pressures, the rapid ionization means that the electron density crosses the resonance point at a rate too fast to allow the beat plasma wave to grow to a large amplitude (again resulting in low levels of backscatter). The pressure range in between these two limits is rather broad as indicated by the sideband measurements.

Estimate of Plasma Wave Amplitude

According to the fluid treatment of Rosenbluth and Liu[2], the early growth of the plasma wave amplitude is governed by the equation

$$\frac{d\varepsilon}{dt} = \alpha_1(t)\alpha_2(t)\,\frac{\omega_p}{4} \tag{1}$$

where $\varepsilon = \delta n/n$ is the wave amplitude and $\alpha = eE/m\omega c = v_0/c$.

The wave amplitude grows linearly with time until it saturates because of relativistic detuning. The saturated amplitude is given by[2]

$$\varepsilon_s = [\tfrac{16}{3}\,\alpha_1(t)\alpha_2(t)]^{1/3} \tag{2}$$

and the time to saturation t_s is determined from [7]

$$\frac{\omega_p}{4}\int_0^{t_s}[\alpha_1(t')\alpha_2(t')]\,dt' = [\tfrac{16}{3}\,\alpha_1(t)\alpha_2(t)]^{1/3} \tag{3}$$

Assuming a linear risetime τ for the laser intensity, $I(t) = It/\tau$ and $\alpha(t) = \alpha(t/\tau)^{1/2}$, the time to saturation is given by

$$\omega_p t_s = 4.87[\tau\,\omega_p/\alpha_1\alpha_2]^{2/5} \tag{4}$$

The saturated electric field amplitude is then calculated from[1] $eE = mc\omega_p\varepsilon_s$.

For 10 J of energy in each of the two wavelengths (9.6 µm and 10.6 µm) in a 1.0 ns pulse focused to a 120 µm spot size, $I_9=I_{10}$ = 4.4 x 10^{13} W/cm^2, and $\alpha_1=\alpha_2=0.06$. With a laser intensity risetime $\tau \approx$ 300 ps, the time to saturation $t_s \approx$ 80 ps and the saturated amplitude $\varepsilon_s \approx 0.17$ giving an electric field gradient of 5.4 GV/m.

Electron Source and Acceleration

The source of electrons used in these experiments was produced by irradiating an aluminum slab target with an auxiliary, high intensity (10^{14} W/cm^2) CO_2 laser beam focused to a 0.1 mm spot (Fig. 1). It has been known for a long time that resonance absorption of high intensity laser light at the critical surface generates a nearly Maxwellian high energy tail in the electron distribution with a maximum energy of approximately 1.0 MeV, and a time duration on the order of the laser pulse risetime ($\tau \approx 300$ ps). Experimental measurements[8] of this emission give a fluence of approximately 10^8 electrons/keV-sr at an energy of 0.5 MeV, the emission being directed in a 5° cone about the target normal. A double-focusing dipole magnet was used to energy select and inject these electrons into the plasma in a direction parallel to the beatwave generating laser beam. With a half-angle acceptance of 50 mrad for the dipole and an energy resolution of $\Delta E/E \approx 0.25\%$ at the dipole output, we are transporting approximately 10^6 electrons to the interaction region.

With the system shown schematically in Fig. 1 and described in this section, we have tested the beatwave concept by accelerating electrons. In order to synchronize the various elements of the system, the optical delay between the beatwave producing laser pulse (main beam in Fig. 1) and the electron producing pulse (auxiliary beam in Fig. 1) was adjusted so that the time of arrival of the electrons at the plasma jet overlapped with the duration of the beat plasma wave in the jet. A multichannel magnetic spectrometer was used to measure both the injected and accelerated electrons in the energy range 0.3 MeV $< E <$ 4.5 MeV, the electron signals being measured with surface barrier detectors.

Preliminary measurements indicated that electrons injected at 0.6 MeV were accelerated to 2.0 MeV. Electron acceleration was observed only when a plasma density of 10^{17} cm^{-3} was attained as determined from the initial gas filling pressure and as supported by the high level of backscattered anti-Stokes sideband signal. Furthermore, acceleration was observed only when the two laser lines (λ = 9.6 µm and 10.6 µm) were incident on the plasma. Finally, energetic electrons were observed only when lower energy electrons were injected into the plasma, confirming that the accelerated electrons observed in these experiments did not originate from the plasma jet as a result of some non-linear process. Since the resonant plasma region is approximately 1.5 mm long, the acceleration observed in these experiments would suggest an electric field gradient of the order of 1 GV/m. In some preliminary shots we have also observed signals up to the 4.5 MeV channel, when electrons were injected at 1 MeV. If confirmed, these observations would suggest electric field gradients of the order of 3 GV/m over a region of approximately 1.5 mm.

Conclusion

We have assembled an experiment to test the laser plasma beatwave accelerator concept. Our approach is totally laser-based, and this gives us some important advantages. Although it still remains a difficult experiment, the complexities are greatly reduced by this approach. Since the region over which the beatwave is excited (approximately equal to twice the Rayleigh length) is limited by the f-number of the focusing optics, we have reason to believe that we can increase this region quite considerably by using longer f-number focusing optics. This would increase the energy gain per stage, without changing the field gradients appreciably. With longer f-number focusing optics, we can reasonably consider using several plasma jets (and hence accelerating regions) created by the same laser beam in a multi-stage configuration. A principal shortcoming of our laser based approach is that the injection energy is limited to approximately 1 MeV. However, for proof-of-principle experiments and for studying the wave-wave and wave-particle interactions, this does not appear to be a serious drawback. In any case a higher energy injection source, such as a 10 MeV linac can be incorporated as an extension of this system in the future.

With this system we have demonstrated the acceleration process in a laser plasma beatwave, but the process needs to be explored further and quantified. Important theoretical aspects of wave-particle interactions need to be verified and experiments need to be devised to study important accelerator aspects of the beatwave concept such as transverse beam dynamics[9,10,11] and beam loading[12].

Acknowledgments

We acknowledge the excellent technical support of M. St-Pierre, F. Levesque, F. Poitras, D.D. Mercier and J. Gauthier. One of the authors (N.A.E.) wishes to thank Drs. J.H. Ormrod, J.C.D. Milton, G.E. Lee-Whiting, L.W. Funk and K.C.D. Chan of AECL for encouragement, support and many stimulating discussions. This work was funded in part by NSERC and FCAR grants.

References

1. T. Tajima and J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979).

2. M.N. Rosenbluth and C.S. Liu, Phys. Rev. Lett. 29, 701 (1972).

3. C.M. Tang, P. Sprangle and R.N. Sudan, Phys. Fluids 28, 1974 (1985).

4. R.J. Noble, Phys. Rev. A 32, 460 (1985).

5. D.J. Sullivan and T. Tajima, in Laser Interaction and Related Plasma Phenomena, edited by H. Hora and G.H. Miley (Plenum, New York, 1984), Vol. 6, p. 1093.

6. B. Stansfield, R. Nodwell and J. Meyer, Phys. Rev. Lett. 26, 1219 (1971); B. Amini and F.F. Chen, Phys. Rev. Lett. 53, 1441 (1985); N.A. Ebrahim, P. Lavigne and S. Aithal, IEEE Trans. Nucl. Sci., NS-47, 2291 (1985); C.E. Clayton, C. Joshi, C. Darrow and D. Umstadter, Phys. Rev. Lett. 54, 2343 (1985); F. Martin, T.W. Johnston and N.A. Ebrahim, Phys. Rev. Lett. 55, 1651 (1985).

7. D.W. Forslund, J.M. Kindel, W. Mori, C. Joshi and J.M. Dawson, Phys. Rev. Lett. 54, 558 (1985).

8. N.A. Ebrahim and C. Joshi, Phys. Fluids, 24, 138 (1981).

9. J.D. Lawson, RAL Report RL83-057 (1983).

10. R. Fedele, U. de Angelis and T. Katsouleas, PPG-887, UCLA (1985).

11. Laser Acceleration of Particles, AIP Conference Proceedings, NO 91, ed., P.J. Channell (1982); Laser Acceleration of Particles, AIP Conference Proceedings, NO 130, eds., C. Joshi and T. Katsouleas (1985).

12. T. Katsouleas, P. Chen, J.M. Dawson, J.J. Su and S. Wilks, PPG-952 UCLA (1986).

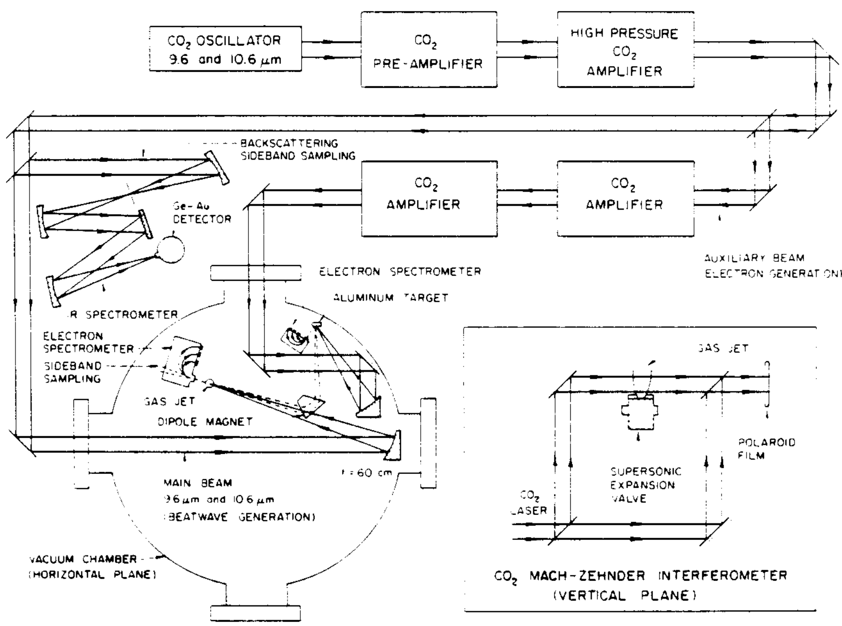

Fig. 1 Schematic of the experimental arrangement.

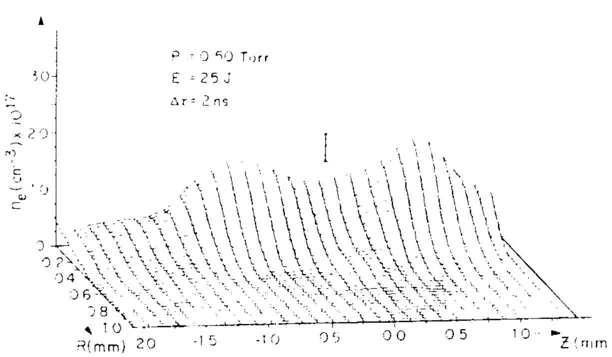

Fig. 2 Measured electron density profile. The main laser beam is incident along the Z-axis, at Z = 0.

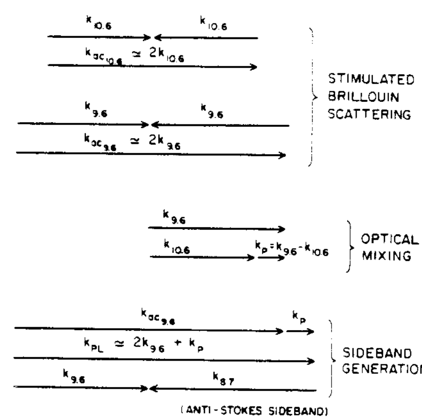

Fig. 4 Generation mechanism for 8.7 μm sideband in the backscatter.

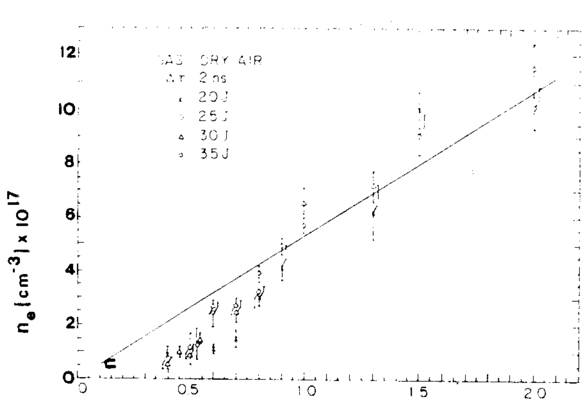

Fig. 3 Electron density as a function of filling pressure for dry air.

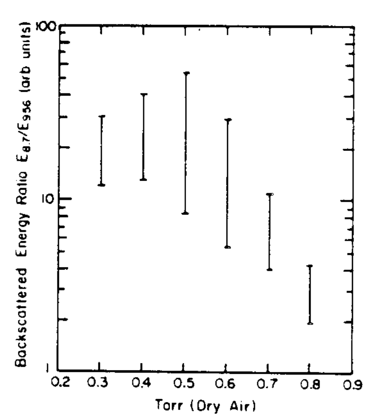

Fig. 5 Ratio of backscattered signals at 8.7 μm and 9.56 μm as a function of filling pressure for dry air.