ELECTRON ACCELERATION BY RELATIVISTIC ELECTRON PLASMA WAVES IN THE LASER PLASMA BEATWAVE ACCELERATOR CONCEPT

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ABSTRACT

An experiment to study the laser plasma beatwave accelerator concept is described. Experimental results are presented to demonstrate the principle of electron acceleration by relativistic electron plasma waves driven by the optical mixing of laser light in a plasma. Electrons injected at 12.5 MeV have been accelerated to 29.0 MeV over a plasma length of approximately 1 cm. This corresponds to an effective accelerating electric field gradient of approximately 1.7 GeV/m.

1. INTRODUCTION

Recently there has been a great deal of interest in studying the behaviour of relativistic electron plasma waves driven by the optical mixing of intense electromagnetic waves because of their potential applications in accelerating particles to ultra-high energies for future high energy particle accelerators (1). In the laser plasma beatwave accelerator concept (2) the electron plasma waves are generated by the non-linear coupling of two intense laser beams of slightly different frequencies propagating through a low-density plasma (3). If the difference frequency of the two laser beams (ω_1,k_1 and ω_2,k_2) is chosen to match the plasma frequency ($\omega_1 - \omega_2 = \omega_p$), the ponderomotive force of the beatwave can resonantly build up the relativistic electron plasma wave. A trailing, relativistic, electron bunch injected into the plasma can be trapped in the potential well of the electron plasma wave and gain considerable energy. Theoretically, accelerating gradients of order $\varepsilon \sqrt{n_e}$ volt/cm are possible, where n_e is the plasma density in cm^{-3} and ε is the density fluctuation $\delta n_e/n_e$. Observations of electron acceleration in laser-driven, relativistic, electron plasma waves have been reported in a number of different experimental configurations where electrons were either self-trapped from a plasma background (4,5) or externally injected from a laser-driven electron source (6) and a low energy linac (7).

Experimental results presented in this paper demonstrate the principle of electron acceleration by relativistic, electron plasma waves driven by the optical mixing of laser light in a plasma. Significant energy gain has been observed in electrons injected from a high-energy linear electron accelerator into a centimetre-length plasma.

2. EXPERIMENTS

(i) Plasma Generation

The experimental arrangement is discussed in detail elsewhere (8,9,10) and only the essential points will be restated in this paper. The short-pulse CO_2 laser facility used in these experiments has been configured for dual-wavelength operation and produces 50 J at 10.59 μm and 10 J at 10.25 μm. These two wavelengths correspond to a resonant plasma density of 1×10^{16} cm^{-3}. The laser pulsewidth is approximately 500 ps full-width at half-maximum (FWHM) with a linear risetime of approximately 200 ps. The laser beam was focused by an off-axis parabolic mirror (f/13.5) to a near diffraction-limited spot with a diameter of approximately 350 μm to yield a peak intensity in vacuum of 1×10^{14} W/cm^2. The plasma was produced by the tunnelling ionization of neutral argon gas in an interaction chamber at a filling pressure 0.2 - 0.4 torr, measured on an MKS, Baratron absolute-pressure transducer, with an accuracy of 0.15%. Full ionization of argon gas (to Z = 1) is attained once the threshold intensity of 6×10^{13} W/cm^2 is exceeded. For peak laser intensities of 1×10^{14} W/cm^2, these experiments are below the threshold for Z = 2 and significant ionization to Z = 2 is not expected (11). Furthermore, since the plasma density is limited to around 1×10^{16} cm^{-3}, beam refraction is not expected to be significant (8,11). The plasma light was imaged onto a charge-coupled-device (CCD) camera and the two-dimensional image recorded on a video-recorder. Dimensions of the observed plasma images suggest an axial plasma length of approximately 1 cm.

(ii) Electron Linear Accelerator

The 12.5 MeV pulsed linear electron accelerator facility consists of a 1.6 m long S-band (3 GHz), $\pi/2$-mode standing-wave structure driven by a 2 MW pulsed magnetron with a pulse duration of approximately 4 μs. A low-impedance, thermionic dispenser-cathode electron gun, driven by an avalanche-transistor, pulser injects 2.3 ns pulses at an energy of 45 keV into the accelerating structure. At a radiofrequency of 3 GHz, the 12.5 MeV electron beam has a microbunch length of 30 ps and an interbunch spacing of 330 ps, with approximately 2×10^8 electrons in a microbunch (for a macropulse current of 100 mA). There are approximately 7 microbunches in a macropulse. If the plasma-wave lifetime is assumed to be of the order of the time to saturation by relativistic detuning of the resonance (~ 140 ps), then single microbunches would be accelerated. The energy spread of the injection beam is ± 2%.

(iii) Electron Transport Beamline and Spectrometer

Extensive calculations (8) with computer programs TRANSOPTR and TRANSPORT (second-order, beam-transport design codes), as well as POISSON and TOSCA (magnetic-circuit design codes) were used to design a doubly-achromatic (beam width and slope independent of momentum in the final image space), double-focusing (equality of the radial and axial image distances) beamline consisting of a quadrupole-triplet lens, three 60° dipole bending magnets and three, quadrupole singlets to transport and match the input beam bunch to the plasma-interaction region. The final quadrupole-singlet lens focused the beam to a focal diameter of approximately 300 - 400 μm with a beam waist that overlapped the laser beam waist at the centre of the main interaction chamber. The electron macropulse and the laser pulse were synchronized to better than 100 ps using a germanium detector located at the centre of the interaction chamber. The accelerated beam from the interaction region was dispersed in a circular pole, broad-range magnetic electron spectrometer (Browne-Buechner) and detected in a seven-channel array of particle detectors. For the present work the electron spectrometer was configured to cover an energy range of 12.5 - 29 MeV in four channels. In these experiments the beam was detected in Faraday cups and the output fed into a multi-channel variable gain amplifier and oscilloscopes.

3. RESULTS

Figure 1 shows the energy spectrum of the accelerated beam for Ar-gas pressure of 280 mtorr. The peak accelerated-electron signal from the detectors (proportional to the charge deposited) at a given energy and normalized to the peak injected electron signal at 12.5 MeV for a single microbunch, is plotted. Different symbols have been used to identify each single-shot energy spectrum. The spectra show a continuous distribution out to 29.0 MeV, which is consistent with the fact that a single microbunch length of 9 mm (30 ps) extends over approximately 28 plasma wavelengths (with a plasma wavelength λ_p ~ 320 μm) and hence particles are injected at all phases. This is analogous to dc beam injection in a conventional electron linac. Null tests were conducted to establish the mechanism for the observed acceleration. Measurements were made with a laser beam and no electrons injected as well as injected electron beam with no laser beam for a static Ar-gas pressure of 280 mtorr. No acceleration was observed in either of the above two cases. Furthermore, tests with the laser and electron beams without Ar-gas in the chamber (i.e. no plasma), or with Ar-gas pressure significantly different from 280 mtorr (e.g. 160 mtorr), also showed no acceleration. We observe no evidence of acceleration for 160 mtorr of Ar-gas because the corresponding electron density (~ 5 x 10^{15} cm^{-3}) is too low for frequency-resonance conditions to be satisfied. No acceleration was observed when electrons were injected into a plasma formed in 280 mtorr of Ar-gas by a single-wavelength laser beam (either 10.59 μm or 10.25 μm). Only the dual-wavelength irradiation with injected electrons showed acceleration.

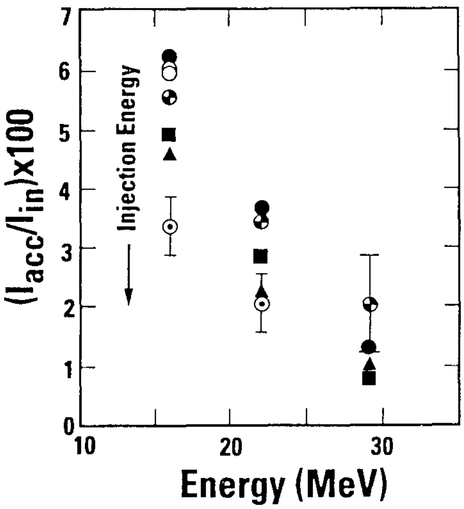

Fig. 1. Energy spectrum of the accelerated-electron beam. The peak accelerated-electron signal (proportional to the charge deposited) is normalized by the peak injected-electron signal at 12.5 MeV for a single microbunch. Filling pressure: 280 mtorr Ar-gas. Different symbols are used to identify each single-shot energy spectrum. Typical noise levels for each of the energy channels are indicated by the error bars.

Figure 2 shows a plot of the normalized, peak accelerated-electron signal for 17.0 MeV electrons as a function of the Ar-gas filling pressure in the range 200 - 350 mtorr. The variation of the accelerated electron signal shows a clear resonance around a filling pressure of 280 mtorr. This pressure corresponds to an electron plasma density of 9 x 10^{15} cm^{-3}, whereas the calculated resonant electron plasma density from the laser wavelengths used in these experiments (10.59 and 10.25 μm) is 1 x 10^{16} cm^{-3}. The discrepancy in plasma density (of about 10%) suggests some ionization of Ar-gas to Z = 2 at the filling pressure of 280 mtorr. Figure 2 shows a small, accelerated-electron signal (down by a factor of about 3) above 280 mtorr which could result from a plasma wave of reduced amplitude as a result of detuning.

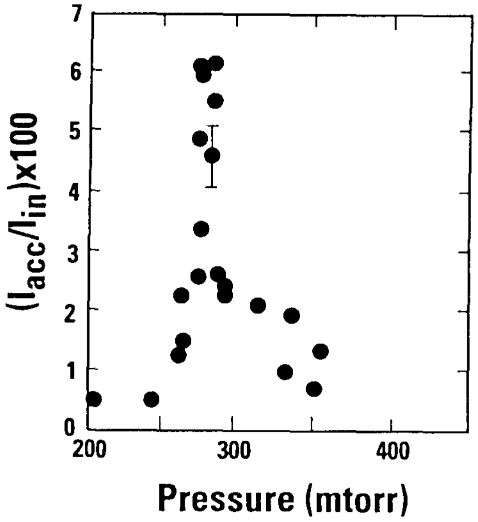

Fig. 2. Variation of the normalized, peak electron signal at 17.0 MeV with Ar-gas filling pressure. Typical noise level is indicated by the error bar.

4. DISCUSSIONS

Estimates based on mode-coupling theory (12) and collisional damping theory (13) suggest that relativistic saturation would dominate. The level at which density fluctuation ($\varepsilon = \delta n_e/n_e$) saturates as a result of the relativistic detuning of the resonance is given by (14)

$$\epsilon_s = \left[\frac{16}{3} \alpha_1(t)\, \alpha_2(t) \right]^{\frac{1}{3}} \qquad (1)$$

where $\alpha = v_0/c = eE/m_0\omega c = 8.5 \times 10^{-10}\ \lambda(\mu m)\ I^{1/2}$ (W/cm^2). Assuming that the laser intensity has a linear risetime τ, the time t_s, for the plasma-wave amplitude to saturate as a result of the relativistic detuning is given by

$$\omega_s t_s = 4.87 \left[\frac{\tau\, \omega_p}{\alpha_1 \alpha_2} \right]^{\frac{2}{5}} \qquad (2)$$

where $\alpha(t) = \alpha\ (t/\tau)^{1/2}$. For our experimental conditions, with the laser intensities $\alpha_1 = 0.09$ and $\alpha_2 = 0.04$, $t_s = 133$ ps, $\varepsilon_s = 0.23$ and $E_s = 0.96 \sqrt{n_e}\ \varepsilon_s = 2.2$ GV/m. With a plasma length of approximately 1 cm this electric-field gradient corresponds to an energy gain of 22 MeV compared to the energy gain of 16.5 MeV (12.5 to 29 MeV) in our experiments.

5. CONCLUSIONS

In conclusion we have demonstrated the principle of electron acceleration by relativistic, electron plasma waves driven by the optical mixing of laser light in a plasma. Effective accelerating electric-field gradients of approximately 1.7 GeV/m have been achieved in centimetre-length plasmas.

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7. REFERENCES

1. J.M. Dawson, Sci. Am. 260, No. 3, 54 (1989).
2. T. Tajima and J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979); C.M. Tang et al. Appl. Phys. Lett. 45, 375 (1984).
3. M.N. Rosenbluth and C.S. Liu, Phys. Rev. Lett. 29, 701 (1972).
4. N.A. Ebrahim et al., IEEE Trans. Nucl. Sci. 32, 3539 (1985); N.A. Ebrahim, Physics in Canada 45, 178 (1989).
5. Y. Kitagawa et al., Phys. Rev. Lett. 68, 48 (1992).
6. N.A. Ebrahim et al. 1986 Linear Accelerator Con. Proc., Stanford, CA, SLAC Report No. 303, p. 552; N.A. Ebrahim et al., J. Appl. Phys. 67, 6742 (1990).
7. C.E. Clayton, et. al. Phys. Rev. Lett. 70, 37 (1993); Clayton et al. Phys. Plasmas, 1, 1753 (1994).
8. N.A. Ebrahim, Research Trends in Physics, Ed. A.M. Prokhorov, AIP (1992), pp. 310 - 351.
9. N.A. Ebrahim, 1992 Linear Accelerator Con. Proc, Ottawa, Atomic Energy of Canada Report, AECL-10728, edited by C.R. Hoffmann (1992), p. 825.
10. N.A. Ebrahim, J. Appl. Phys. (to be published).
11. W.P. Leemans et al., Phys. Rev. Lett. 68, 321 (1992).
12. C. Darrow et al., Phys. Rev. Lett. 56, 2629 (1985).
13. R. Bingham et al., Plasma Phys. Contr. Fusion 29, 115 (1987); J.P. Matte et al., Plasma Phys. Contr. Fusion 30, 395 (1988).
14. D.W. Forslund et al., Phys. Rev. Lett. 54, 558 (1985).