REVIEW OF CURRENT RESEARCH IN LASER AND PLASMA-BASED ACCELERATION

Nizar A. Ebrahim
AECL Research, Chalk River Laboratories
Chalk River, Ontario, Canada, K0J 1J0

ABSTRACT

The idea of using lasers and/or plasmas for acceleration of particle beams represents a revolutionary concept in accelerator science. One of the main attractions of all such concepts is the significantly higher field gradients that have been predicted by theory and particle simulations. This paper will review the complex and sophisticated experiments that have been designed to test theoretical predictions, and explore the implications of these ideas for a useful ultra-high energy particle accelerator. Reference will be made to the Chalk River facility, which consists of a short pulse, dual wavelength, CO_2 laser system (300 - 500 ps, 9.6 and 10.6 μm or 10.3 and 10.6 μm) that can generate focal power densities in excess of 10^{14} W/cm^2. A plasma source (static gas fill or a supersonic gas jet) at a density of 10^{16} - 10^{17} cm^{-3} is produced by tunneling ionization of neutral hydrogen gas in the laser fields. An S-band, 10 MeV linac injects 30 ps electron microbunches with approximately 10^8 - 10^9 electrons in each microbunch. The electron beam is transported in a double-focusing, doubly-achromatic beamline and focussed to a spot less than 900 μm in diameter in the interaction region. A modified Browne-Buechner electron spectrometer and a multichannel detector complement a full range of laser plasma diagnostics.

1. INTRODUCTION

The physical mechanism underlying the laser plasma beatwave concept is the optical mixing of laser light in a plasma, which excites a large-amplitude relativistic electron plasma wave as a result of the beat ponderomotive force.[1] This force, which acts on the plasma electrons and causes them to bunch, is directed along the propagation direction of the electromagnetic waves, is periodic and originates in a non-zero **v** x **B** force of the electromagnetic waves, as shown in Fig. 1. The ponderomotive force is given by[2]

$$F_{NL} = -\frac{\omega_{pe}^{\ 2}}{\omega_0\omega_1}\nabla\frac{<|E_0 + E_1|^2>}{8\pi} \qquad (1)$$

where $\omega_{pe} = (4\pi n_e e^2/m_e)^{1/2}$ is the electron plasma frequency, n_e is the plasma electron density, ω_0 and ω_1 are the laser frequencies and E_0 and E_1 are the electric fields of the two laser beams propagating through a low-density plasma. If the difference frequency of the lasers (ω_1 - ω_2) is chosen to match the plasma frequency (ω_{pe}), the ponderomotive force of the beatwave can resonantly build up the relativistic plasma wave.

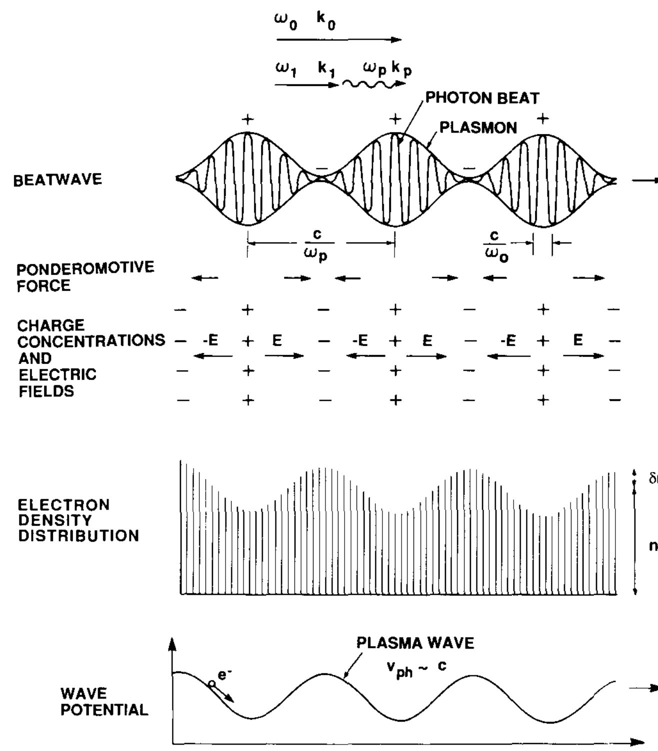

Fig. 1 Schematic diagram of the beatwave, ponderomotive force, concentrations of the positive and negative charges, the associated electric fields, electron density distribution, and the ponderomotive wave in the plasma.

In the plasma wakefield accelerator (PWFA) concept, the plasma waves are excited by a short, intense electron bunch propagating through a high-density plasma.[3] The space charge force of the electron bunch displaces the plasma electrons and generates a wake of plasma oscillations with a phase velocity that is equal to the driving electron bunch velocity, which is very close to the velocity of light. An alternative to using an electron bunch is to inject an extremely short but intense laser pulse into a low-density plasma, as in the laser wakefield accelerator (LWFA) concept.[4] The ponderomotive force of the laser pulse envelope initially expels the plasma electrons both radially and axially, resulting in plasma oscillations as the returning electrons overshoot their initial positions. The acceleration of particles in the three concepts is identical. A trailing relativistic electron bunch, injected into the potential well of the plasma wave at the appropriate phase, remains synchronized to the wave and is accelerated.

We can estimate the maximum possible amplitude of the plasma wave by considering the maximum possible bunched electron density or density fluctuation δn_e. For a background plasma electron density of n_e, the maximum possible density fluctuation $\delta n_e = n_e$ in Fig. 1. From Poisson's equation

$$\nabla \cdot E = 4\pi\rho = -4\pi e \delta n_e = -4\pi e n_e \quad \delta n_e \sim n_e \tag{2}$$

$$\nabla^2 \phi \approx 4\pi e n_e \tag{3}$$

and

$$|e\phi| \sim \frac{4\pi n_e e^2}{m_e} \frac{m_e}{k^2} = \frac{\omega^2_{pe}}{c^2 k^2} m_e c^2 \tag{4}$$

The maximum electric field

$$|E_{\max}| = |k\phi_{\max}| = \frac{\omega_{pe} m_e c^2}{ce} = 0.94 \sqrt{n_e} \ \ V/cm \tag{5}$$

where n_e is the plasma electron density in cm^{-3}.

As the plasma wave amplitude increases, the relativistic mass increase of the oscillating electrons $m_e \rightarrow \gamma m_e$, results in a change in the plasma frequency $\omega_{pe}^2 \rightarrow \omega_{pe0}^2/\gamma$, where ω_{pe0} is the plasma frequency with the rest mass, and γ is the relativistic Lorentz factor defined by the mean electron velocity in the wave. The plasma frequency ω_{pe} no longer matches the driver frequency (ω_0 - ω_1) and this dephasing causes the amplitude growth to slow, stop and then reverse.

Although significant progress has been made in the development of theory and computer simulations of various laser acceleration concepts, many important aspects need to be verified experimentally. Important problems that have been under investigation in the last few years are techniques for the creation and diagnostics of large-scale, high-density, homogeneous plasmas, the generation and diagnostics of large-amplitude relativistic electron plasma waves, the coupling of these waves to lower-phase velocity electron and ion waves, and the trapping and acceleration of electrons.

2. EXPERIMENTAL FACILITY

As a reference experiment, we describe the Chalk River laser particle acceleration facility described in greater detail elsewhere.[5] The short pulse, dual wavelength, CO_2 laser system (300 - 500 ps, 9.6 and 10.6 μm or 10.3 and 10.6 μm) can generate focal power densities in excess of 10^{14} W/cm^2, and consists of a hybrid TEA (transversely excited atmospheric-pressure) oscillator and pre-amplifier system (Fig. 2), a GaAs Pockel's cells switch system and a 3 atm, large-aperture, high-pressure amplifier (Fig. 3).

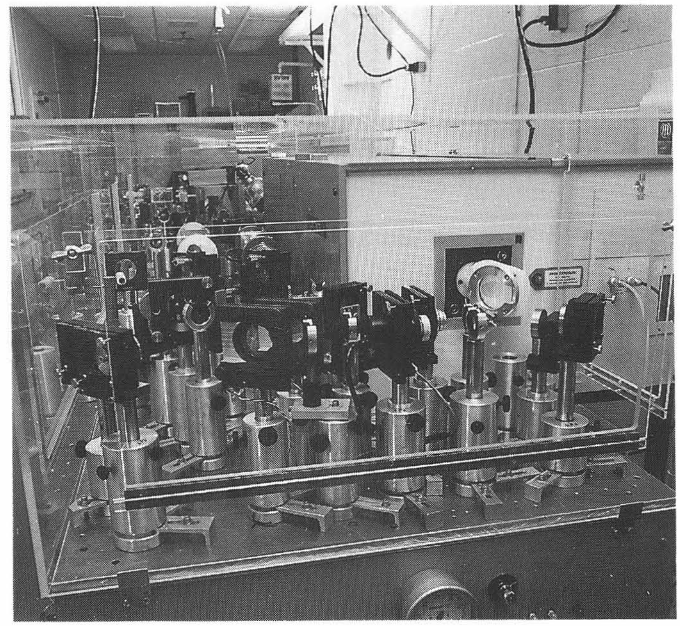

Fig. 2 The oscillator and the pre-amplifier sections of the CO_2 laser facility.

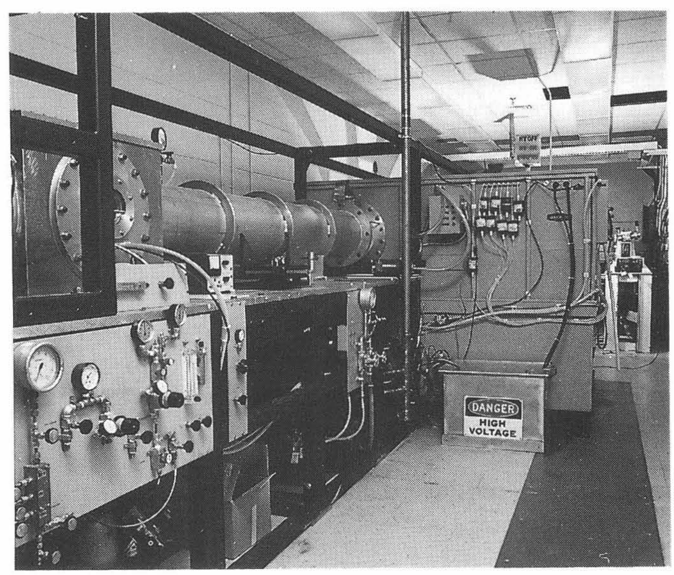

Fig. 3 The high-pressure CO_2 laser amplifier system.

The 10 cm diameter beam from the final amplifier is focused into the interaction chamber by an f/15, 150 cm focal length, off-axis parabola (Fig. 4), where tunneling ionization of the background gas produces a plasma over a region on the order of twice the Rayleigh length.

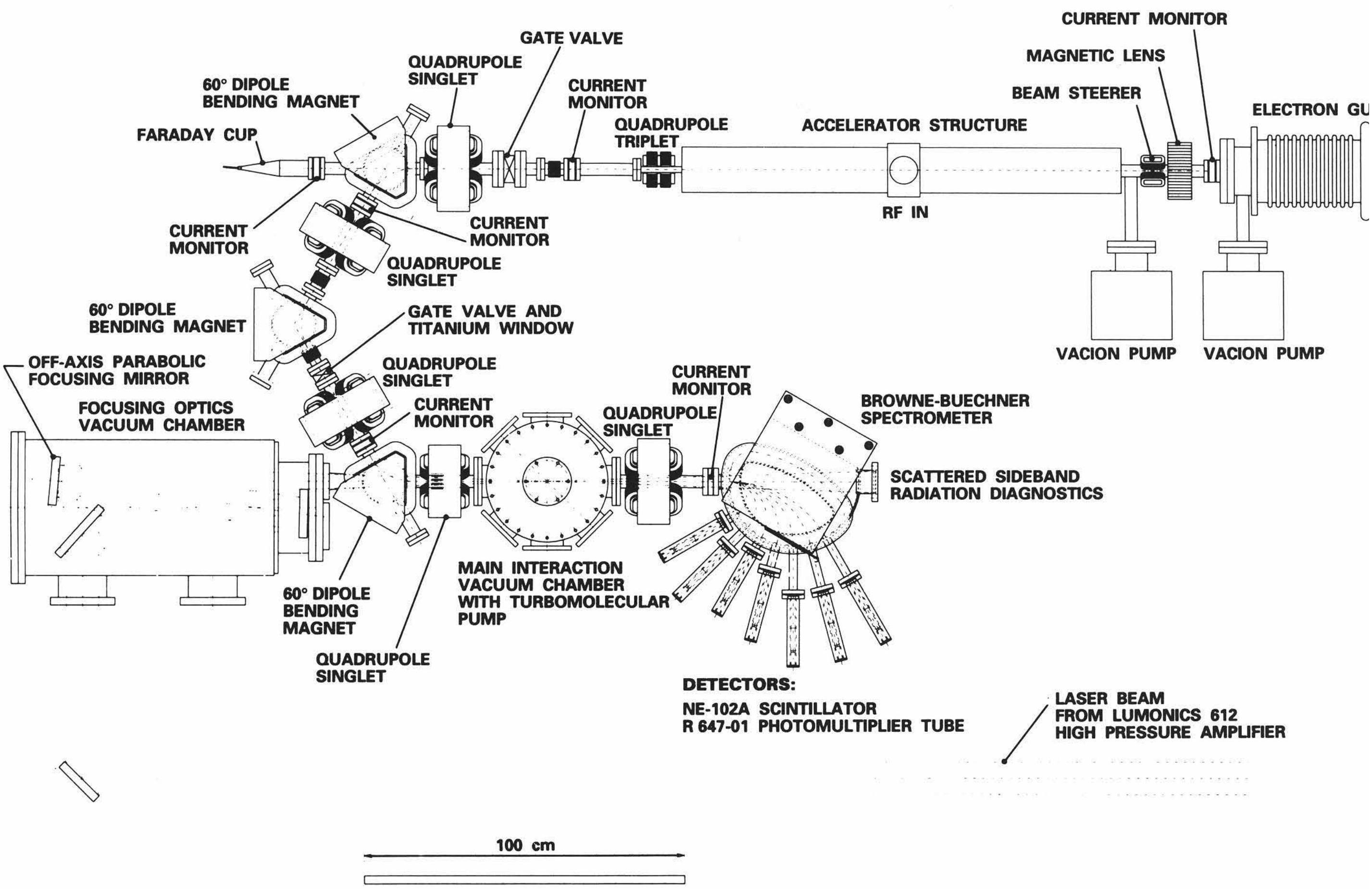

Fig. 4 Schematic of the Chalk River laser acceleration facility.

The pulsed linear electron accelerator is shown schematically in Fig. 4. The output electron beam at the exit of the last accelerating cavity is focused by a quadrupole triplet magnet, turned through 180° in a beamline consisting of three dipole bending magnets and three quadrupole singlets, and brought to a focus in a vacuum interaction chamber by a final focusing quadrupole singlet magnet. The accelerated electrons from the laser interaction are dispersed in a magnetic electron spectrometer and detected with an array of electron detectors.

Figure 5 shows the layout of the experimental area, and Fig. 6 shows the electron spectrometer and the detector array.

The radial effective root-mean-square (RMS) beam half-widths along the beamline downstream from the linac, as calculated with TRANSPORT and TRANSOPTR, are shown in Fig. 7. Figure 8 shows the measured beam spot size in the interaction region and a typical beam current time profile.

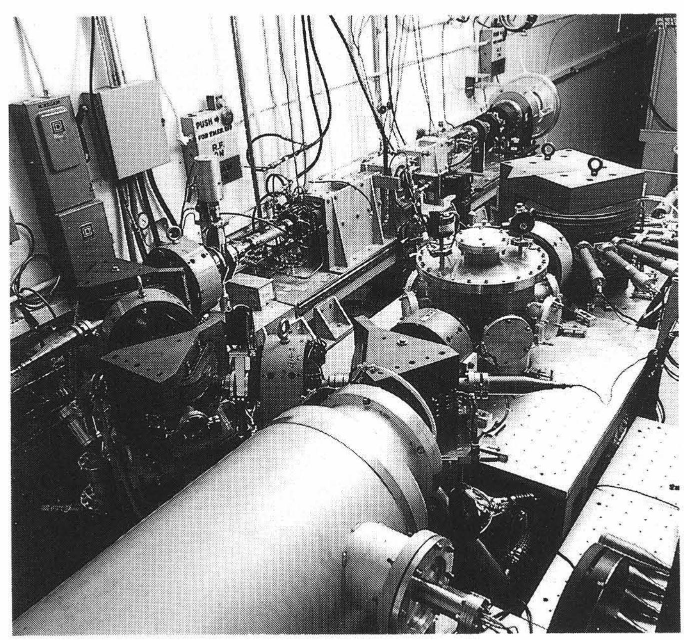

Fig. 5 Layout of the experimental area.

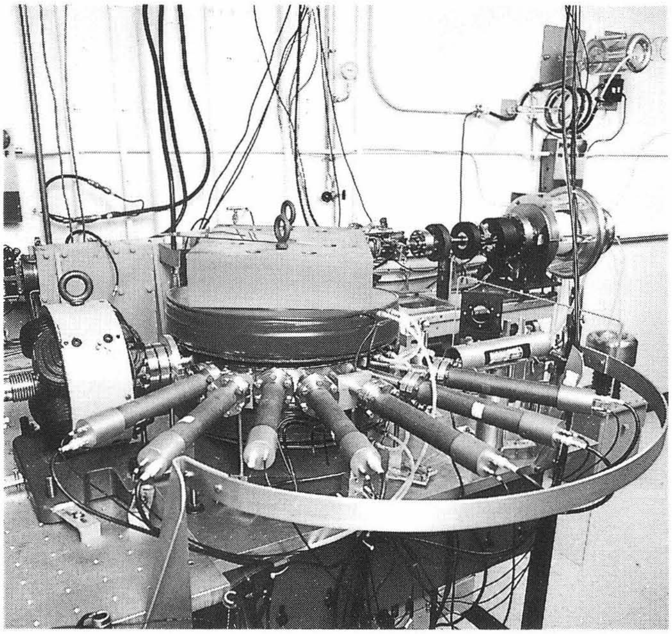

Fig. 6 Electron spectrometer and detector array.

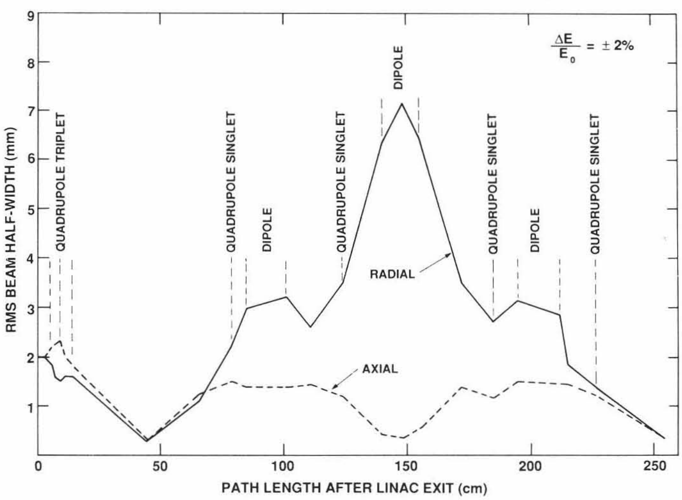

Fig. 7 Computer-calculated radial and axial beam profiles.

3. DISCUSSION

(i) Plasma Generation

High-density plasmas for laser particle acceleration experiments have been produced either by laser irradiation of thin carbon films ("exploding foils")[6,7] with θ-pinch discharges,[8] or by the tunnelling and multiphoton ionization of a neutral gas by a focused laser beam.[9,10,11,12] Of these, only the last technique appears to be suitable, since exploding foil plasmas are limited in size ($L \sim C_s\tau \sim 0.5$ mm, where C_s is the ion acoustic speed and τ is the laser pulse duration), and θ-pinch plasmas are not sufficiently homogeneous and tend to have trapped magnetic fields that scatter injected low-energy electrons.

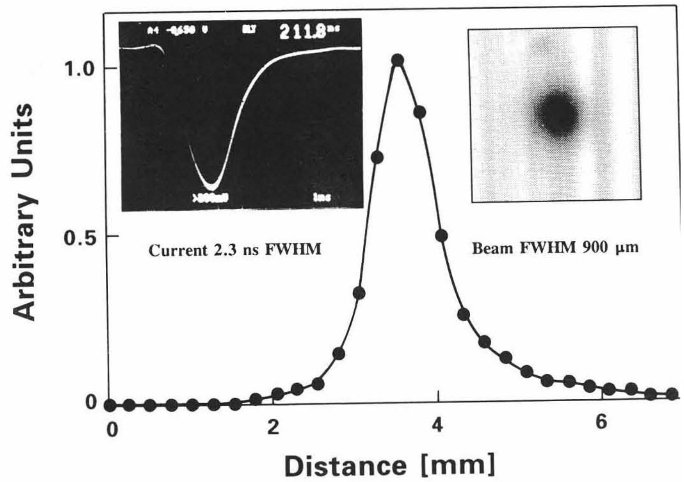

Fig. 8 Measured electron beam spot size in the interaction region.

The nonresonant ionization of a uniform gas or partially-ionized plasma by intense laser fields is separated into two regimes by the Keldysh tunneling parameter[13]

$$\gamma_K = \left(\frac{E_{ion}}{2\Phi_{pond}}\right)^{1/2} \qquad (6)$$

where E_{ion} is the ionization potential of the atom or ion and Φ_{pond} is the ponderomotive potential of the laser (average kinetic energy of an electron in the laser field)

$$\Phi_{pond}(eV) = \frac{e^2E^2}{4m_e\omega^2} = 9.33 \times 10^{-14}\, I\, \lambda^2 \qquad (7)$$

where E is the electric field strength of the laser in V/cm, I is the focused laser irradiance in W/cm^2 and λ is the laser wavelength in microns.

For short wavelength lasers (ruby or neodymium) at moderate laser intensities we are in the $\gamma_K > 1$ regime, and ionization is described as a multiphoton ionization process where an atom or an ion simultaneously absorbs N photons

$$A^{n+} + N\hbar\omega \rightarrow A^{n+1} + e^- \qquad (8)$$

where $N\hbar\omega > E_{ion}$.

With high-laser-intensity, long-wavelength lasers (typical of CO_2 laser experiments), we are in the $\gamma_K < 1$ regime and ionization is described as a tunneling process. Macroscopic plasmas of sufficient homogeneity have now been produced in a number of experiments using short pulse, high-power CO_2 lasers[9,10] ($n_e = 10^{16}$ cm^{-3}) and Nd:YAG lasers[11] ($n_e = 10^{17}$ cm^{-3}) with plasma dimensions on the order of 1.5 cm.

However, a problem with laser beam refraction occurs at higher densities in plasmas produced by multiphoton ionization, as a result of a plasma-induced refractive index change. This effect limits the intensity of the focused laser beam to a value close to the threshold for multiphoton ionization. The conditions for significant laser beam refraction can be derived from considerations of Gaussian laser beam propagation in a medium with threshold intensity for ionization.[5]

$$\frac{\delta n_e}{n_c} = \frac{\lambda^2}{\pi^2 \omega_0^2} \qquad (9)$$

For electron density change greater than that given in Eqn. (9), laser light propagating through the plasma will diverge, thereby limiting the laser intensity to a value near the threshold for multiphoton ionization. Equation (9) shows that in CO_2 laser experiments with $\lambda = 10.6\ \mu m$ and a focal spot $\omega_0 \approx 100\ \mu m$, laser beam refraction from multiphoton ionization will be significant for plasma electron densities in excess of 10^{16} cm^{-3}.

(ii) Wave Generation

Observations of the electron plasma waves have been made by Thomson scattering of an external probe beam or the main beam. Measurements of the frequency-shifted scattered power give a direct measure of the wave amplitude. Recent experiments on Thomson scattering with external probe beams[8,11] and sideband scattering of the main laser beam[9,11,12] give an estimate of wave amplitudes that corresponds to electric field gradients of approximately 1 GeV/m, compared to 20 MeV/m in conventional rf-driven particle accelerators.

(iii) Electron Acceleration

Observations of electron acceleration in laser-driven relativistic electron plasma waves have been reported in a number of different experimental configurations.[6,7,9,12] Studies[6] with exploding foil plasma targets have observed electron energies up to 1.5 MeV from the forward Raman instability excited by a single-frequency, high-intensity ($> 10^{14}$ W/cm^2) laser beam. The electrons were self-trapped from the background plasma. Self-trapped electrons up to 3.0 MeV were observed in a dual-wavelength laser beatwave experiment.[7] Recent experiments[12] using tunnel-ionized plasmas have reported observations of self-trapped electrons with energies up to 20 MeV. Acceleration of externally injected 0.6 MeV electrons from a laser-driven source to 1.5 MeV were reported in a laser beatwave experiment[9] using a 1.5 mm length tunnel-ionized plasma source (Fig. 9). More recently,[14] 2.0 MeV electrons from a linac injector have been accelerated to 9 MeV over a 7-mm plasma length. These experiments suggest electric field gradients on the order of 1 GeV/m.

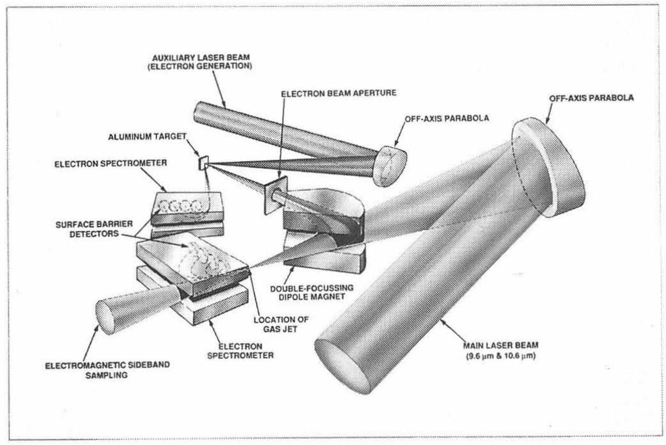

Fig. 9 Experimental arrangement to demonstrate acceleration of externally injected electrons.

4. CONCLUSIONS

Large-amplitude, high-phase velocity electron plasma waves have been generated by high-power laser beams. Electron acceleration by relativistic plasma waves has been observed in a number of experimental configurations. Macroscopic plasma generation by powerful laser beams (tunneling and multiphoton ionization) is being actively investigated, since these studies are critical to experiments on laser particle acceleration. Major advances in femtosecond, terrawatt laser technology in the past few years will seriously impact this work in the future.

5. REFERENCES

1. T. Tajima and J.M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
2. F.F. Chen, Introduction to Plasma Physics and Controlled Fusion, 2nd ed., Vol. 1, (1984).
3. P. Chen, J.M. Dawson, R.W. Huff and T. Katsouleas, Phys. Rev. Lett. **54**, 693 (1985).
4. P. Sprangle, E. Esarey, A. Ting and G. Joyce, Appl. Phys. Lett. **53**, 2146 (1988).
5. N.A. Ebrahim, Research Trends in Physics, Ed. A.M. Prokhorov, AIP (1992).
6. C. Joshi et al., Phys. Rev. Lett. **47**, 1285 (1981).
7. N.A. Ebrahim, P. Lavigne and S. Aithal, IEEE Nucl. Sci. **32**, 3539 (1985).
8. C. 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).
9. N.A. Ebrahim and F. Martin, J. Appl. Phys. **67**, 6742 (1990).
10. W. Leemans et al., Phys. Rev. Lett. **68**, 321 (1992).
11. F. Amiranoff et al., Phys. Rev. Lett. **68**, 3710 (1992).
12. Y. Kitagawa et al., Phys. Rev. Lett. **68**, 48 (1992).
13. L.V. Keldysh, Zh. Eksp. Teor. Fiz. **47**, 1945 (1964) [Sov. Phys. JETP **20**, 1307 (1965)].
14. K. Marsh, C. Joshi and T. Katsouleas, Private Communication (1992).