A 100 MeV Proof-of-Principle Laser Wakefield Accelerator Experiment*

A. Ting, A. Fisher, R. Fischer, J. Grun, J. Krall, E. Esarey anf P. Sprangle
Beam Physics Branch, Plasma Physics Division, Naval Research Laboratory
Washington, DC 20375-5346

D. Umstadter and G. Mourou
Center of Ultrafast Optical Science, University of Michigan
Ann Arbor, MI 48109

Abstract We present an initial design of a proof-of-principle experiment on the Laser Wakefield Accelerator (LWFA). The experiment will utilize the NRL Table-Top Terawatt (T^3) laser system as the driver for the wakefield in a pulsed-valve gas jet plasma, and a ~1 MeV Febetron as the electron beam injector. The LWFA will be operated in the self-modulated regime [1] where enhanced acceleration gradients and extended interaction distances can be achieved. Numerical simulations demonstrate that with the present parameters of the T^3 laser, peak accelerating gradients can reach >300 GeV/m and single stage energy gain of >100 MeV can be attained.

I. INTRODUCTION

Plasma-based accelerators have recently been the subject of intense research because of their potential for high accelerating gradients, compact size and low cost compared with conventional rf-driven accelerators [2]. While conventional rf-driven accelerators are limited to fields on the order of 100 MeV/m, plasma accelerators have been shown experimentally to support gradients of ~1 GeV/m [3] in the Plasma Beat Wave Accelerator (PBWA), and are predicted theoretically and numerically to support gradients exceeding 300 GeV/m [1] in the LWFA.

Two configurations of the LWFA have been proposed, (i) the "standard" LWFA [4] and (ii) the "self--modulated" LWFA.[1] In the recently proposed self-modulated LWFA, enhanced acceleration is achieved via resonant self-modulation of the laser pulse. This occurs when (i) the laser pulse extends axially over several plasma wavelengths, $L >> \lambda_p$, and (ii) the peak laser power satisfies $P \geq P_c$, where P_c is the critical power [5] for relativistic optical guiding, $P_c[GW] \approx 17(\lambda_p/\lambda_0)^2$ and λ_0 is the laser wavelength. At fixed laser parameters, both conditions can be met by choosing a sufficiently high plasma density, n. This is the case since $P_c \propto 1/n$ and $\lambda_p \propto 1/\sqrt{n}$. Operation in the self-modulated regime has very significant advantages over the standard configuration.

The newly developed T^3 laser technology [6] is capable of delivering the short (< 1 ps), ultrahigh power (> 1 TW) laser pulses required by the LWFA. Simulations based on the NRL T^3 laser parameters and the self-modulated LWFA configuration indicate that accelerating fields in excess of 300 GeV/m and electron energies in excess of 100 MeV can be obtained in a single stage.

II. APPROACH

A schematic of a proof-of-principle LWFA experiment is shown in Fig. 1.

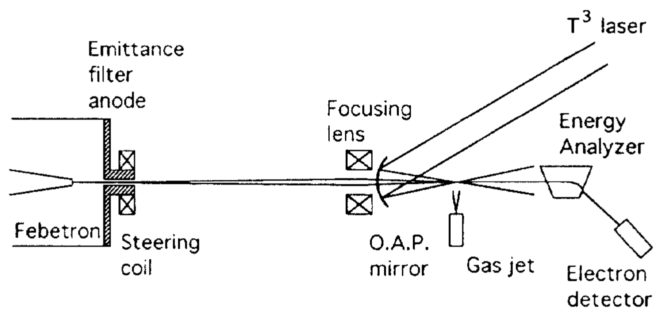

Fig. 1. Schematic of the proof of principle LWFA experiment. An electron beam from a compact injection accelerator is accelerated by the laser plasma wakefield and then energy resolved with an electron spectrometer.

A pulsed-valve is used to deliver a high density gas jet inside an evacuated chamber. The gas jet is ionized through multiphoton ionization to form a plasma column by either a precursor pulse or the prepulse of the driver laser pulse. The driver laser pulse is focused into the plasma column with appropriate optics such as an off-axis paraboloid (O.A.P.) at high intensities to generate the wakefield. The characteristics of the plasma wakefields are measured with the Thomson scattering diagnostics. An electron beam with energy high enough to be trapped by the wakefield is injected into the plasma after being transported and focused. Accelerated electrons are detected and analyzed with a magnetic spectrometer for the energy spectrum. The parameters for the experiment are shown in Table I.

III. APPARATUS

This experiment consists of five major components: A) the NRL T^3 laser to drive the wakefield, B) the NRL Febetron electron accelerator for electron injection into the wakefield, C) a gas jet plasma source to support the wakefield, D) a Thomson scattering diagnostics for characterizing the

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wakefield, and E) an electron spectrometer to measure the energy gain of the injected electrons.

Laser parameters:	
Wavelength	1.054 μm
Energy	~1.5 J
Pulse length	~750 fs
Focal spot radius (F/6 optics)	~10 μm
Intensity	~1.3 × 10^{18} W/cm^2
Wakefield parameters:	
Plasma density	~1.25 × 10^{19} cm^{-3}
Plasma wavelength	~10 μm
Acceleration gradient	>300 GeV/m
Interaction length	~0.2 cm
Pump depletion length	~2 cm
Phase detuning length	~0.4 cm
Energy gain	>100 MeV
Electron beam parameters:	
Energy	~1 MeV
Current	~10 A
Pulse length	~50 ns
Focused beam radius	~100 μm
Number of electrons trapped	~10^5

Table I. Typical laser, wakefield, and electron beam parameters for the proof-of-principle LWFA experiment.

A. Laser Diver

The NRL T^3 laser is based on the chirped pulse amplification (CPA) concept [6] which takes advantage of the fact that laser amplifiers can better amplify a long pulse than a short pulse. By incorporating frequency chirping in a long pulse, the amplified pulse can be compressed by use of gratings into a short pulse with much higher intensity. The NRL T^3 laser system has been operational since Oct. 1992. It has an energy per pulse of ~1.5 J and a pulse length of ~750 fs, giving a laser power of ~2 TW. The high quality laser beam produces a spot size of ~20 μm at 1.4 times diffraction limited with an f/6 lens, giving a peak intensity of ~1.3 × 10^{18} W/cm^2. It also has a high contrast ratio of ~10^{-6} between the amplitude of the prepulse to the central peak. The repetition rate is one pulse/4 minutes.

B. Electron Beam Injector

In a practical LWFA, the electron bunch must be synchronized in both time and space to the wakefield for maximum accelerating gradient and minimum energy spread. However, for a proof-of-principle experiment, the minimum required bunch length is determined by having enough electrons to be accelerated for detection. The NRL Febetron electron beam, which has a pulse length of 50 ns, will behave as if it is CW, and therefore eliminate the problem of synchronization. The Febetron is capable of producing several kA's of beam current. However, to avoid perturbing the plasma with a high current electron beam, the Febetron beam current will be limited to ~10 A by mismatching the diode and collimating the beam with a pinhole aperture (few mm). The collimation also acts as an emittance filter and produces a high quality electron beam which can be focused with a magnetic lens for better matching to the acceptance of the plasma wakefield.

C. Plasma Source

By operating the LWFA in the self-modulated regime, substantially higher gradients and longer interaction distances can be achieved. This can be accomplished by using a higher density plasma, while utilizing the same parameters for the laser and the electron beam. By incorporating an ultrasonic nozzle to a pulsed-valve gas jet, neutral gas density of > 1 × 10^{19} cm^{-3} can be obtained. The corresponding critical power for relativistic focusing for this plasma density is 1.7 TW and the plasma wavelength is only 10 μm. Many periods of plasma wakefields can be excited in the 750 fs laser pulse.

D. Wakefield Characterization

Coherent Thomson scattering [7] will be used to detect the plasma wakefields and measure its frequency and amplitude. In this process, a light wave is scattered by a plasma wave. The scattered light wave is frequency shifted by the plasma wave frequency. Thomson scattering from the plasma wave is performed with a synchronized collinear longer laser pulse (~20 mJ, ~100 - 150 ps, of either 1 μm (ω) or 0.5 μm (2ω) light) derived from a separate but synchronized transform-limited laser developed at CUOS. The wavelength shift for an electron plasma density of 10^{16} - 10^{19} cm^{-3} is found from phase matching conditions to be approximately $\Delta\lambda$ = 30 - 950 Å for ω and 8 - 240 Å for 2ω light, which can be measured with a conventional double grating spectrometer.

The amplitude of the plasma wave, $\Delta n/n$, is obtained from the amplitude of the scattered light through the Bragg scattering formula [8]. Assuming a plasma wave amplitude of 10% and probe pulse energy of 20 mJ, as many as 10^8 - 10^{14} photons will be scattered. It is expected that the plasma wave amplitude can be increased to beyond the nonrelativistic cold plasma wavebreaking limit, $\Delta n/n = 1$, where nonlinear behavior of the plasma wave is prominent. The nonlinear regimes of wakefield generation can be studied by measuring the harmonics of the plasma wave frequency in the spectrum of the scattered light [9].

E. Electron Energy Analyzer

The energy of the accelerated electrons will be measured as a function of laser intensity, plasma density, and acceleration distance. Because the electron bunch is much longer than the plasma wavelength, electrons would interact with the wakefield at arbitrary points along the wave and thus experience arbitrary gradients. A large energy spread (1 -100 MeV) would be expected regardless of the input electron energy spread. A magnetic electron spectrometer is most suitable for analyzing electron beams with large energy spreads due to its large dynamic range. By allowing a collimated electron beam to enter a narrow gap separating two magnetic poles, the beam velocity can be determined from the resulting radius of curvature. The curved electrons can be detected with solid state detectors, scintillators or Cerenkov detectors. Magnetic monochromators, where the electrons go though fixed radius of curvature, are more suitable for lower energy electrons (1-10 MeV). For higher energy electrons, the energy spectrum can be studied with constant field magnetic spectrometers, attenuation filters, and Cerenkov cells. Direct observation of the electrons in a Wilson cloud chamber is also possible [3].

IV. DISCUSSION

The number of electrons that may be trapped by the wakefield can be estimated as follows. Assuming the wakefield has a spatial extent of ~ 20 μm and an amplitude of a fraction of the nonrelativistic wave breaking field, the acceptance of the wakefield in phase space is typically an elongated vertical ellipse because of the very large radial wakefield that is excited together with the longitudinal accelerating wakefield. On the other hand, the electron beam's phase space area is typically a horizontal elongated ellipse as it comes out of the Febetron accelerator. For a good emittance electron beam (~5 π mm mrad), it can be focused down to ~200 μm. The electron beam's phase space area is thus rotated and squeezed into a vertical ellipse (still wider than the ellipse formed by the wakefield acceptance, and the system is under focused). The overlapping area of the electron beam emittance and the acceptance of the wakefield is approximately given by the square of the ratio of the radial wakefield radius to the focused electron beam radius. The ratio is ~ 5×10^{-3}. For an electron beam with ~10 A of current, a picosecond laser wakefield will overlap with ~6.2×10^7 electrons. Taking into account that only one quarter of each wakefield period has both accelerating and focusing wakefields, an interaction length of 2 mm, and the emittance-acceptance overlapping ratio estimated above, the number of electrons that can be trapped and accelerated is ~ 2×10^5. Such intensities of the accelerated electron may be conveniently detected with solid state detectors or scintillators and photo-multipliers.

Although the minimum injection energy required for trapping of the electrons in the accelerating potential is only ~200 keV, higher injection energy is required to overcome scattering of the electrons by the initial radial wakefield in an extended plasma region [10]. A plasma column with sharp boundary will allow a rapid buildup of the wakefield within the scalelength of the plasma boundary when the driver laser arrives. Numerical simulations have demonstrated that with a good quality electron beam and a sharp boundary plasma column, electrons with ~1 MeV will be trapped by the wakefields. The boundary of the gas jet is more well defined at the earlier stages of the gas jet evolution. It is important to synchronize the ionizing laser and the driver laser with respect to the gas jet so as to create a plasma with a sharp boundary. This will facilitate more efficient trapping of the electrons in the injection electron beam.

V. CONCLUSIONS

We have presented a preliminary design on a 100 MeV proof-of-principle experiment of the LWFA operating in the self-modulated regime. The experiment is based on the NRL T3 laser driver and the NRL Febetron electron accelerator. We have discussed the various diagnostics for wakefield characterization and electron energy analysis. We have also discussed the importance of using a gas jet as the plasma source, and the propagation and focusing of the electron beam for better trapping of the electrons. A proof-of-principle LWFA experiment that can produce very high accelerating gradients and final energies appears to be feasible.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

[1] J. Krall, A. Ting, E. Esarey and P. Sprangle, submitted to *Phys. Rev. E*, and these proceedings.
[2] See, e.g., *Proc. 3rd Intl. Workshop on Advanced Accelerator Concepts, Port Jefferson, NY, 1992*, ed. by J. Wurtele, (AIP, NY), to be published.
[3] C.E. Clayton, K.A. Marsh, A. Dyson, M. Everett, A. Lal, W.P. Leemans, R. Williams and C. Joshi, *Phys. Rev. Lett.* **70**, 37 (1993).
[4] T. Tajima and J. Dawson, *Phys. Rev. Lett.* **43**, 267 (1979); L.M. Gorbunov and V.I. Kirsanov, *Sov. Phys. JETP* **66**, 290 (1987); P. Sprangle, E. Esarey, A. Ting and G. Joyce, *Appl. Phys. Lett.* **53**, 2146 (1988).
[5] C.E. Max, J. Arons and A.B. Langdon, *Phys. Rev. Lett.* **33**, 209 (1974); P. Sprangle, C.M. Tang and E. Esarey, *IEEE Trans. Plasma Sci.* **PS-15**, 145 (1987).
[6] G. Mourou and D. Umstadter, *Phys. Fluids B* **4**, 2315 (1992).
[7] C. Clayton, C. Joshi, C. Darrow and D. Umstadter, *Phys. Rev. Lett.* **54**, 2343 (1985).
[8] R. E. Slusher and C. M. Surko, *Phys. Fluids* **23**, 472 (1980).
[9] D. Umstadter, R. Williams, C. Clayton and C. Joshi, *Phys. Rev. Lett.* **59**, 292 (1987).
[10] P. Mora, *Phys. Fluids B* **4**, 1630 (1992).