LASER PLASMA ACCELERATION EXPERIMENT AT THE NAVAL RESEARCH LABORATORY*

D. Kaganovich,# D. Gordon, and A. Ting, Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375

Abstract

A relativistically intense laser pulse is focused into a gas jet and quasi-monoenergetic electrons emitted at a 37 degree angle with respect to the laser axis are observed. The average energy of the electrons was between 1 and 2 MeV and the total accelerated charge was about 1 nC emitted into a 10 degree cone angle. The electron characteristics were sensitive to plasma density. The results are compared with three dimensional particle-in-cell simulations. This electron acceleration mechanism might be useful as a source of injection electrons in a laser wakefield accelerator.

INTRODUCTION

The laser wakefield accelerator (LWFA) [1, 2] is one of several advanced accelerator concepts that takes advantage of the extremely high electric fields that can be supported in a plasma. The LWFA produces a large amplitude plasma wave whose phase velocity approaches the speed of light and can trap electrons and accelerate them to high energies. Most experiments to date [3-6] have operated in the self-modulated (SM) regime, which produces very large accelerating gradients (~10^{11} V/m) but poor quality electron beams with large energy spread. More recently, quasi-monoenergetic acceleration of particles from the background plasma has been observed in simulations [7-9] and experiments [10-12] operating in a shorter pulse regime. To get more stable electron production controlled injection and acceleration are required. Such conditions have already been demonstrated [13, 14]. Scientists agree that staging and external injection are the key issues for commercial quality laser wakefield accelerators.

EXPERIMENT

To measure the electron energy and angular distributions we have constructed the experimental system shown in Figure 1. This system measures the electron energy spectrum for any angle between 0 and 50 degrees. It is also capable of measuring the angular distribution of the ejected electrons. The main part of the system is the electron spectrometer that is mounted on a rotational stage in the vacuum chamber. The axis of rotation is designed to coincide with the position of the gas jet, where the electrons are generated. A collimator and an electromagnet are mounted on the rotational stage and a scintillator plate is banded around the backside of the electromagnet. Clockwise rotation of the stage from 0 to 50 degrees allows scanning of the electron energy distribution for this range of angles, whereas counterclockwise rotation opens the entire scintillator area for angular distribution studies. In the experimental studies we have used both helium and nitrogen gases and have been able to change the plasma densities from 10^{18} cm^{-3} to 5×10^{19} cm^{-3}. The plasma density was measured by Raman back scattering.

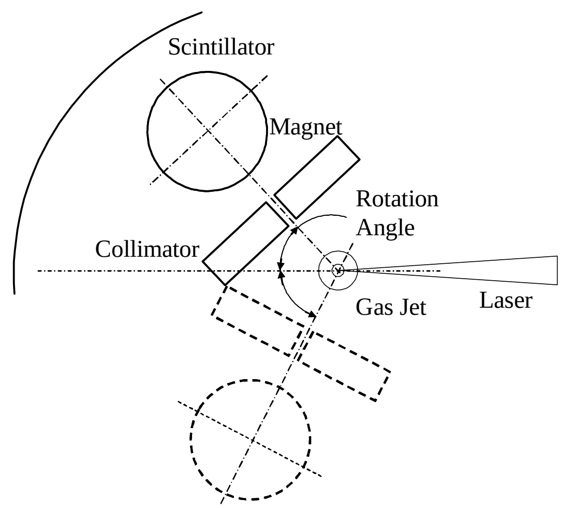


Figure 1: Experimental system with rotational arm electron spectrometer.

The 50 fs laser beam was focused to the 0.5 mm diameter gas jet using an F#10 off-axis parabolic mirror. The power of the laser was continuously changed from 3 to 6 TW, corresponding to a peak laser intensity that ranged from 4 to 8 $\times10^{18}$ W/cm^2. The polarization of the laser was in the plane of rotation of the electron spectrometer.

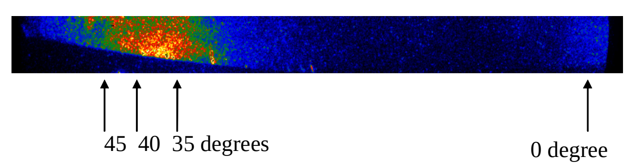
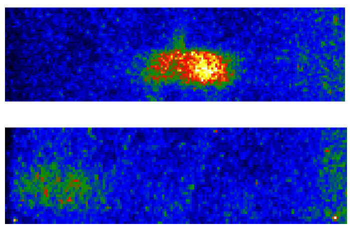


Figure 2: Angular distribution of the ejected electrons.

The electrons from the laser plasma interaction propagated through the collimator and were deflected by the electromagnet. The front side of the scintillator (BC400) is covered with two layers of thin aluminum foil. Its back side was imaged by an Andor ICCD camera.

*Work supported by DOE and ONR
LET Corporation, Washington DC

Initially, we studied the angular distribution of the injected electrons. The collimator and magnet were rotated away from the possible electrons trajectories and thus the scintillator was exposed to detect electrons ejected between 0 to 50 degrees. We checked the angular distribution for different plasma densities of helium and nitrogen gases and for different intensities of the laser. The most interesting angular distribution was found to be for helium plasma densities between 1.5 – 2 $x10^{19}$ cm^{-3} and laser intensity near $5x10^{18}$ W/cm^2. For these set of parameters the majority of the ejected electrons was offset from the laser propagation direction by 35-40 degrees, as



(a)

(b)

Figure 3: Scintillator images at 40 degree of electron spectrometer setup. No magnetic field (a), 0.2 kG (b).

shown in Fig. 2. Most of the ejected electrons were concentrated in a 10 degrees cone around the 37 degrees line. The charge of ejected electrons was obtained from

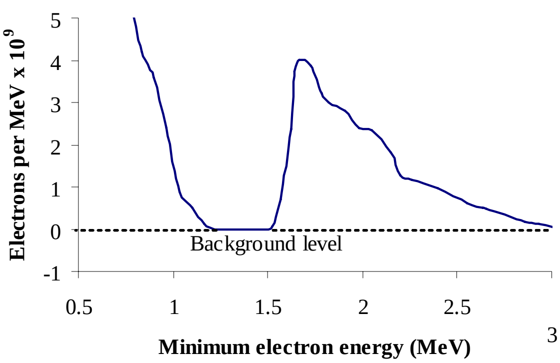


Figure 4: Experimental electron spectrum at 40^0.

the scintillator signal that was cross-calibrated against a fast current transformer. The total charge ejected into this 40 degrees direction varied between 0.5 to 1.5 nC. All other directions in the area covered by the scintillator received less than 0.5 nC of charge.

To obtain the energy distribution of the ejected electrons we rotated the electron spectrometer to this 40^0 angle using the collimator. Figure 3 shows the section of the scintillator where the energy of these electrons was detected and measured. In the absence of the magnetic field, the total charge of the electron pulse at 40^0 angle was about 300 pC [Figure 3(a)]. In the presence of an applied magnetic field, the high-energy segment of these electrons has a narrow energy distribution that is shown in Figure 3(b). At 0.2 kG magnetic field the energy of detected electrons was above 1.5 MeV and total charge of the pulse approximately 50 pC (Figure 4).

DISCUSSION

The generation of electrons in a high intensity laser plasma interaction is a complex process involving a number of simultaneous effects including relativistic self-focusing, self-modulation instabilities, the formation of electron cavitation regions, and particle trapping. To understand this rich interplay of nonlinear physics we have carried out three dimensional, fully relativistic, fully electromagnetic particle-in-cell simulations using turboWAVE. The code was run using the fully explicit option where the optical period is resolved. The laser pulse was initialized at best focus with a quiver momentum of 1.8*mc*, a full width half maximum (FWHM) pulse width of 55 fs, and a 6 micron FWHM spot size. The pulse was incident on a pre-ionized plasma with electron density 2 x 10^{19} cm^{-3}. The simulation was carried out on a 1600 x 256 x 256 grid for 16000 time steps with 8 particles per cell. The time step was 0.1 fs and the cell size was 0.04 x 0.36 x 0.36 microns. The simulation was carried out on 256 processors of an IBM cluster 1600 for about 15 hours.

To characterize the simulated electrons 2 dimensional cuts in phase space are often plotted. However, when low energy particles are being considered care must be taken to avoid confusing ejected particles with those that are simply undergoing the usual quiver motion in the laser field. To avoid this confusion, we wrote out phase space data excluding particles within 6 microns of the axis. The p_z-p_x phase plane, where z is the propagation axis and x is the polarization axis, is shown in Fig. 5(a). As observed experimentally, there is a relatively high density of particles propagating at an angle of about 45 degrees with respect to the laser axis. The fact that the highest momentum of these particles is approximately equal to the quiver momentum, and that they lie on the parabola characteristic of particles quivering in a laser field, suggests that the quiver momentum has been somehow preserved in a population of particles escaping the laser focal spot. This is shown in Fig. 5(b) where electrons with the quiver momentum appear behind the laser pulse.

These electrons are ideal candidates for injection into the acceleration stage. In the present experiments the measured charge of these electrons was significantly lower than 1 nC, because of the small acceptance angle of the collimator. However, with the collimator removed, the total charge of these energetic electrons is expected to be substantially higher, since the acceptance angle of the capillary is wider than that of the collimator [13]. The angle between the laser beam and ejected electrons makes it easy to couple the injection and acceleration stages. The gas jet could be placed very close to the capillary but the injection laser beam will still be terminated on the capillary electrode to avoid damaging the capillary.

1-4244-0917-9/07/$25.00

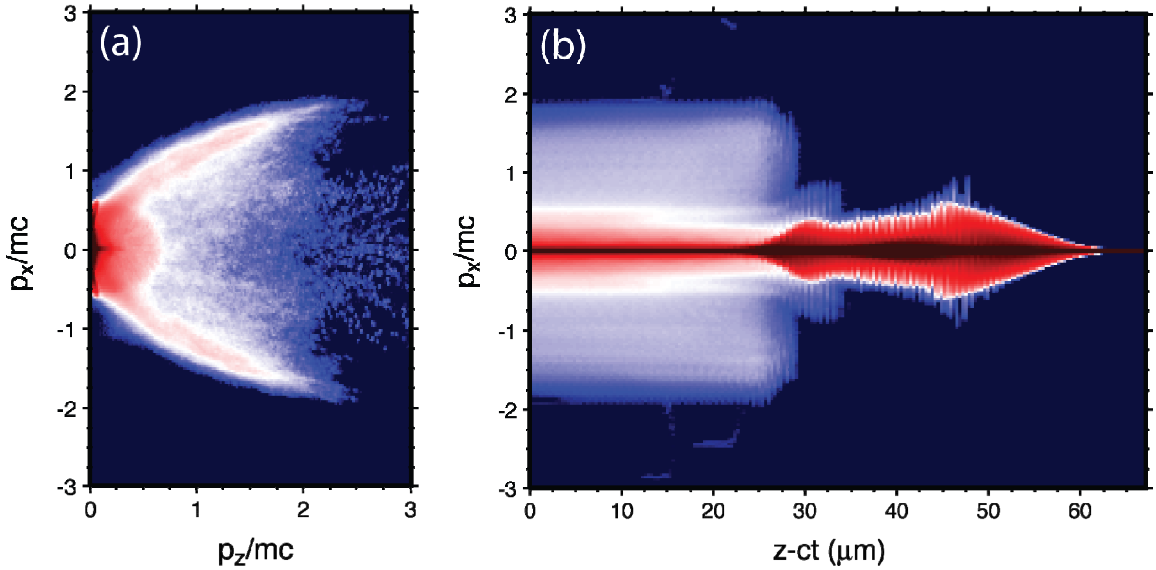


Figure 5: Time integrated phase space plots of electrons outside the laser focus showing (a) high density of particles at 45 degree propagation angle and (b) electrons at the quiver momentum appearing behind the laser pulse. The laser energy is predominantly in the region between z-ct = 30 and z-ct = 50. The color map is referenced to a log scale.

CONCLUSION

In conclusion, substantial numbers of quasi-monoenergetic electrons propagating at a 40 degree angle with respect to the laser axis have been ejected from a helium gas jet irradiated by a 3-6 TW, 50 fs laser pulse. These electrons cannot be explained by the Laser Ionization and Ponderomotive Acceleration (LIPA) [15] mechanism because the ionization potential of the gas is too small. Three dimensional PIC simulations suggest that steepening of the back of the laser pulse causes some electrons to retain a portion of their quiver momentum after the laser passes. The high charge, large ejection angle, and narrow energy spread of these electrons make them a suitable candidate for injection into a channel guided laser wakefield accelerator.

REFERENCES

[1] T. Tajima and J. M. Dawson, Phys. Rev. Lett., 43, pp. 267-270, 1979.

[2] P. Sprangle, E. Esarey, A. Ting, and G. Joyce, Appl. Phys. Lett., 53, pp. 2146-2148, 1988.

[3] K. Nakajima, et. al., Phys. Rev. Lett., 74, pp. 4659-4662, 1995.

[4] D. Umstadter, S. Y. Chen, A. Maksimchuk, G. Mourou, and R. Wagner, Science, 273, pp. 472-475, 1996.

[5] A. Ting, et. al. Phys. Plasmas, 4, pp. 1889-1899, 1997.

[6] D. F. Gordon, et. al., Phys. Rev. Lett., 80, pp. 2133-2136, 1998.

[7] A. Pukhov and J. Meyer-ter-Vehn, Appl. Phys. B, 74, pp. 355-357, 2002.

[8] A. Zhidkov, J. Koga, K. Kinoshita, and M. Uesaka, *Phys. Rev E*, 69, pp. 035401 1-4, 2004.

[9] F. S. Tsung, R. Narang, W. B. Mori, C. Joshi, R. A. Fonseca, L. O. Silva, Phys. Rev. Lett. 93, Art. No. 185002, 2004.

[10] S. P. D. Mangles, C. D. Murphy, Z. Najmudin et al., Nature, 431, pp. 535-538 2004.

[11] C. G. R. Geddes, Cs. Toth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary and W. P. Leemans, Nature, 431, pp. 538-541 2004.

[12] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J.-P. Rousseau, F. Burgy and V. Malka, Nature, 431, pp. 541-544 2004.

[13] D. Kaganovich, A. Ting, D. F. Gordon, R. F. Hubbard, T. G. Jones, A. Zigler, P. Sprangle, Phys. Plasmas, 12 (10): Art. No. 100702, 2005.

[14] J. Faure, C. Rechatin, A Norlin, A, Lifshitz, Y. Glinek and V. Malka Nature 444, 737, 2006.

[15] C. I. Moore, *et. al.*, Phys. Rev. Lett., 82, pp. 1688, 1999.