THE EFFECTS OF A DENSITY MISMATCH IN A TWO-STAGE LWFA*

B.B. Pollock†, G.R. Tynan, UCSD, San Diego, CA 92093, USA
F. Albert, C. Filip, S.H. Glenzer, J. Meinecke, A. Pak, J.E. Ralph
LLNL, Livermore, CA 94550, USA
C.E. Clayton, C. Joshi, K.A. Marsh, J. Shaw, UCLA, Los Angeles, CA 90095, USA
K.L. Herpoldt, University of Oxford, Oxford, United Kingdom
D.H. Froula, Laboratory for Laser Energetics, Rochester, NY 14623, USA

Abstract

A two-stage Laser Wakefield Accelerator (LWFA) has been developed, which utilizes the ionization induced injection mechanism to produce high energy, narrow energy spread electron beams when the electron density is equal in both stages. However, when the densities are not equal these high quality beams are not observed. As the electron density varies across the interface between the adjacent stages the size of the ion cavity is expected to change; this results in either a reduction of the peak electron energy (for a density decrease), or in the exclusion of previously trapped charge from the first wake period (for a density increase). The latter case can be overcome if the interaction length before the density interface exceeds a threshold determined by the densities in each stage, and may provide a mechanism for enhanced energy gain.

INTRODUCTION

Laser Wakefield Accelerators (LWFA) rely on the interaction of short duration, high intensity laser pulses with low density, typically low-Z (such as He or H_2), gases to produce high accelerating gradient structures for generating high energy electron beams [1]. The atoms are tunnel ionized early in the rising edge of the laser pulse, and the ponderomotive force of the laser pushes electrons radially outward. After the laser pulse passes, electrons are pulled back toward the axis by the space charge force of the ions, which are stationary on this timescale due to their inertia. In the so-called "blow-out" regime of LWFA (where the laser normalized vector potential $a_0 > 2$), the radius to which electrons are expelled (and of the corresponding nearly spherical ion cavity) is given by $R = 2\sqrt{a_0}(c/\omega_p)$ [2], where c is the vacuum speed of light and ω_p is the electron plasma frequency. The resulting plasma wave (the "wake") propagates behind the laser pulse with a phase velocity nearly equal to laser group velocity in the plasma.

If electrons gain enough longitudinal momentum to be traveling at the wake phase velocity before crossing the laser axis, they can become self-trapped at the back of the ion cavity and begin to accelerate due to its longitudinal electric field. These electrons begin to outrun the wake, and cross the cavity center after a dephasing length $L = (2/3)(n_{crit}/n_e)R$; here the sign of the electric field reverses and the electrons begin to decelerate ($n_{crit} = 1.75 \times 10^{21} cm^{-3}$ for 800 nm laser light). The maximum energy gain has been shown to be $E(GeV) = 0.37P_{TW}^{1/3}(n_e/10^{18}cm^{-3})^{-2/3}$ for 800 nm laser light [2].

It is evident that in order to access electron energies exceeding 1 GeV with conventional laser systems (<100 TW) electron densities approaching $\sim 10^{18}$ cm^{-3} are required. Previous studies have shown that electron self-trapping is not an effective injection mechanism at these densities [3]. Ionization induced injection [4, 5], which is enabled by adding percent level concentrations of high-Z dopant gas to the low-Z background, has enabled trapping at electron densities as low as 1.3×10^{18} cm^{-3} and peak electron energies of $\sim$1.5 GeV from a centimeter-scale plasma [6]. However, the electron energy spectrum was very broad due to continuous injection of electrons into the wake.

The present work is concerned with reducing the energy spread of a high energy beam by separation of the injection and acceleration processes, and has resulted in the development of a two-stage LWFA. Charge is initially injected over a limited distance via ionization induced injection in a He-N_2 mixture, and is then further accelerated in a pure He region without broadening the energy spectrum. Matching of electron density in these independent stages is critical for generating high quality, high energy electron beams. The consequences of a non-uniform density along the interaction length are examined by considering a density step at the interface between the stages. It will be shown that stepping down in density reduces the overall energy gain of the system, while stepping up can provide enhanced energy gain. However, in the latter case charge must be accelerated a minimum distance before the step to remain in the first wake period after the interface, and some charge will always be lost.

EXPERIMENT DESIGN

Consider an electron trapped at the rear of the ion cavity (one radius R from the center of the cavity). The electron slips forward in the cavity as it accelerates, and reaches the center of the cavity after one dephasing length L in the lab frame. If during this period there is an abrupt change in

---

* This work was performed under the auspices of the Department of Energy by the Lawrence Livermore National Laboratory, the University of California at San Diego, and the University of California at Los Angeles under Contracts No. DE-AC52-07NA27344, No. DE-FG03-92ER40727, No. DE-FG02-92ER40727, No. DE-FC02-07ER41500, and No. DE-FG52- 09NA29552; NSF Grants No. PHY-0936266 and No. PHY-0904039. This work was partially funded by the Laboratory Directed Research and Development Program under project tracking code 08-LW-070.

† pollock6@llnl.gov

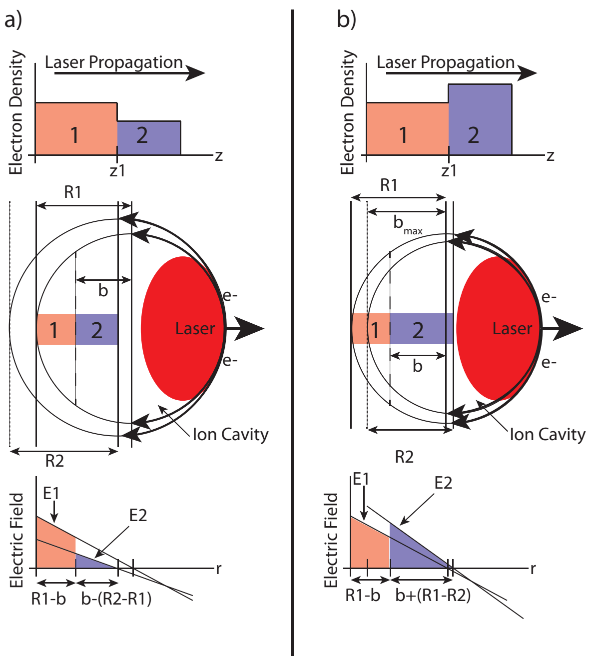

Figure 1: Schematic representation of the effects of a density step in a LWFA gas target. The laser propagates a distance z1 in the target at density n1, forming a blown-out ion cavity with radius R1. Electrons trapped at the rear of the cavity (and at the beginning of the target) have traveled a distance R1-b in the cavity when the laser reaches z1 in the target (the case z1=L corresponds to electrons reaching the cavity center, where b=0, and dephasing). a) The density is reduced at z1, causing the cavity radius to increase to R2 and the cavity center to shift toward the electrons. b) The density increases at z1, causing the blow-out radius to decrease to R2 and the cavity center to shift away from the electrons.

the electron density, which will be represented as a density step for this discussion, the radius of the ion cavity will change to the size corresponding to the density after the step. This process is assumed to be sufficiently fast (on the order of the pulse duration) to be instantaneous for the electrons residing inside the cavity. Since the cavity forms from front to back, the center of the cavity shifts relative to the electrons, modifying the remaining useful accelerating region of the interaction.

We first examine the case of a step down in density, illustrated in Fig. 1a, where electrons have been accelerated over the distance z1 in the lab frame (corresponding to a distance of R1-b in the cavity). The size of the cavity increases after the step, and the cavity center moves away from the laser pulse by (R2-R1). The remaining accelerating region in the cavity is shorter than b, so electrons will dephase after a shorter distance than the initial dephasing length. Additionally, the longitudinal electric field in the lower density region is reduced from that of the high density region. These two effects together act to reduce the maximum energy gain achievable in the system. Furthermore, electrons that gained the maximum possible energy and dephased in the first region (b=0) now reside past the center of the cavity, where the electric field decelerates electrons.

Conversely, if the density increases after the propagation distance z1, the cavity radius decreases. Fig. 1b shows that under these conditions the cavity center slips toward the laser pulse, lengthening the remaining accelerating region from b to b+(R1-R2). Since the density is higher in this region the electric field is increased, and these effects now increase the maximum possible energy gain. Even electrons that have reached dephasing at the time the density step occurs can see an increased energy gain. Note the distance bmax=2(R1-R2) in Fig. 1b; this is the maximum cavity region that can remain before the step to prevent charge from residing outside of the first wake period after the density transition. The criterion placed on the propagation distance is then $z1 \geq L1(1-(bmax/R1))$. If the step occurs before this point, the rear of the high density cavity will form ahead of the electrons; this will cause the electrons to reside in the decelerating field portion of the next period of the wake.

In a two-stage LWFA experiment, should a density step occur it would be at the interface between the stages. If the first stage (the injector) is filled to sufficiently high density He for self-trapping to occur, then a transition to lower density He in the second stage (the accelerator) could be used to terminate the injection. While this may produce a narrower energy spectrum than a constant density He experiment, it comes at the expense of peak energy. However, taking advantage of ionization induced injection in the first stage would allow for trapping at low density, where the density in the accelerator can then be increased to improve energy gain. In order to maintain a limited energy spread, an upper limit on the accelerator density would be the self-trapping threshold of He. There will now be a trade-off between energy spread and total charge, as only the electrons that travel the required length in the injector will remain in the first wake period after the transition. For injector densities between 2-3x10^{18} cm^{-3} and an accelerator density of 4x10^{18} cm^{-3}, the benefit to attempting the density increase is not more than a 5% increase in peak energy to preserve all charge within 10% of the peak energy. Therefore, our experiment attempts to equalize the densities in the injector and accelerator until more reliable trapping at densities below 1x10^{18} cm^{-3} is demonstrated and significant benefit from a higher density accelerator can be realized.

EXPERIMENT SETUP

These experiments are performed with a two-stage gas cell at the Jupiter Laser Facility, Lawrence Livermore National Laboratory, using the 800 nm Ti:Sapphire Callisto laser system. The gas cell allows for the composition of the gas target to be varied along the length of the cell, and for the density in each stage to be independently varied. The first stage (the injector) is filled with a mixture of 99.5% He and 0.5% N_2, and its length is variable from 1-5 mm.

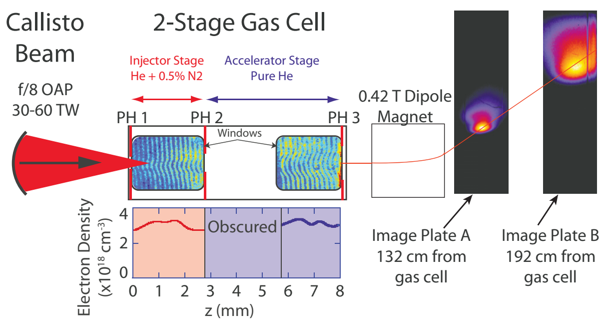

Figure 2: Schematic of the experiment setup showing the 800 nm Callisto laser beam (in red), the two-stage gas cell, a typical interferogram with the Abel inverted density profile of the interferogram, the dipole magnet (20 cm long, centered 66 cm from the exit of the gas cell), and the deflected electron trajectory (red line) onto the image plates (located 132 cm and 192 cm from the exit of the gas cell). The Callisto laser beam is focused by an f/8 off-axis parabola 750 μm past the 500 μm diameter entrance aperture (PH1) of the injector stage of the gas cell. The injector and accelerator stages are separated by a 1 mm diameter aperture (PH2), and the exit aperture of the accelerator stage is 2 mm diameter (PH3).

The second stage contains pure He, and is adjustable from 5-10 mm in length. The adjacent stages are separated by a 1 mm diameter aperture. The Callisto laser delivers up to 250 TW of laser power in a 60 fs pulse, of which $\sim$30% is coupled into a 15 μm FWHM spot.

The energy of the accelerated electrons is measured by a spectrometer consisting of a 0.42 T dipole magnet and two image plates. The vertical deflection of the electron beam is recorded on each image plate, allowing for a unique measurement of the electron energy and deflection angle from the laser axis at the plasma exit [7]. A 100 fs probe beam is employed in a Mach-Zehnder interferometer to measure the electron density along the cell.

RESULTS

Careful density matching between both stages of the cell is found to be critical for producing high quality electron beams, where a <5% energy spread, 460 MeV electron beam has been produced for equal electron densities of 3×10^{18} cm^{-3} (these results are published elsewhere). When the density is decreased from 3×10^{18} cm^{-3} in a 4 mm injector stage to 2.6×10^{18} cm^{-3} in a 5 mm accelerator stage, as in Fig. 3a, a peak electron energy of 160 MeV is observed. This energy is reduced from the maximum observed energy primarily because the gas the cell length was longer than the dephasing length, and electrons lost energy in the front of the wake. The calculated energy gain for this configuration is 190 MeV. Of greater concern is the additional charge behind the peak; in the case of a higher density injector a small downstream flow of the nitrogen dopant is expected, which allows additional trapping after the interface. This directly contributes to broadening the electron beam energy spread.

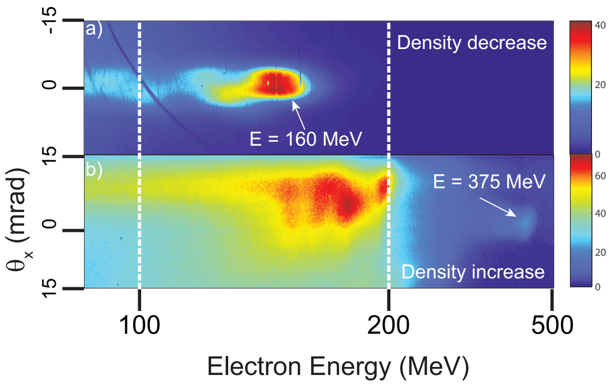

Figure 3: a) The electron density is reduced from 3×10^{18} cm^{-3} in the injector stage to 2.6×10^{18} cm^{-3} in the accelerator stage. b) The electron density is increased from 3.4×10^{18} cm^{-3} in the injector stage to 4×10^{18} cm^{-3} in the accelerator stage. The coupled laser powers are 55 TW and 65 TW, respectively.

Increasing the density from 3.4×10^{18} cm^{-3} in the injector stage to 4.0×10^{18} cm^{-3} in the accelerator stage, as in Fig. 3b, produced a peak energy of 375 MeV. The length of the accelerator was increased from 5 mm to 1 cm for this experiment, so the high energy electrons likely reached dephasing and had begun to decelerate before the gas cell exit. We suspect that the high charge feature that peaks at 200 MeV is from He self-trapping, since 4.0×10^{18} cm^{-3} is our experimentally determined He self-trapping threshold.

REFERENCES

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

[2] W. Lu, M. Tzoufras, C. Joshi, F.S. Tsung, W.B. Mori, J. Vieira, R.A. Fonseca, and L.O. Silva, Phys. Rev. ST Accel. Beams 10 (2007) 061301.

[3] D.H. Froula, C.E. Clayton, T. Döppner, K.A. Marsh, C.P.J. Barty, L. Divol, R.A. Fonseca, S.H. Glenzer, C. Joshi, W. Lu, et.al., Phys. Rev. Lett. 103 (2009) 215006.

[4] A. Pak, K.A. Marsh, S.F. Martins, W. Lu, W.B. Mori, and C. Joshi, Phys. Rev. Lett. 104 (2010) 025003.

[5] C. McGuffey, A.G.R. Thomas, W. Schumaker, T. Matsuoka, V. Chvykov, F.J. Dollar, G. Kalintchenko, V. Yanovsky, A. Maksimchuk, K. Krushelnick, et.al., Phys. Rev. Lett. 104 (2010) 025004.

[6] C.E. Clayton, J.E. Ralph, F. Albert, R.A. Fonseca, S.H. Glenzer, C. Joshi, W. Lu, K.A. Marsh, S.F. Martins, W.B. Mori, et.al., Phys. Rev. Lett. 105 (2010) 105003.

[7] B.B. Pollock, J.S. Ross, G.R. Tynan, L. Divol, S.H. Glenzer, V. Leurent, J.P. Palastro, J.E. Ralph, D.H. Froula, C.E. Clayton, et.al., “Two-Screen Method for Determining Electron Beam Energy and Deflection from Laser Wakefield Acceleration,” PAC’09, Vancouver, May 2009, WE6RFP101, p. 3035 (2009).