LASER WAKEFIELD ACCELERATION BEYOND 1 GeV USING IONIZATION INDUCED INJECTION*

K.A. Marsh, C.E. Clayton, C. Joshi, W. Lu, W.B. Mori, A. Pak, UCLA, Los Angeles, CA 90024

L.O. Silva, GoLP, Lisbon, Portugal

N. Lemos, GoLP, Lisbon, Portugal; UCLA, Los Angeles, CA 90024, U.S.A.

R.A. Fonseca, S. de Freitas Martins, Instituto Superior Tecnico, Lisbon, Portugal

F. Albert, T. Doeppner, C. Filip, D. Froula, S.H. Glenzer, D. Price, J. Ralph, LLNL, Livermore CA 94551, U.S.A

B.B. Pollock, UCSD, La Jolla, CA92093; LLNL, Livermore, CA 94551, U.S.A.

Abstract

A series of laser wakefield accelerator experiments leading to electron energy exceeding 1 GeV are described. Theoretical concepts and experimental methods developed while conducting experiments using the 10 TW Ti:Sapphire laser at UCLA were implemented and transferred successfully to the 100 TW Callisto Laser System at the Jupiter Laser Facility at LLNL. To reach electron energies greater than 1 GeV with current laser systems, it is necessary to inject and trap electrons into the wake and to guide the laser for more than 1 cm of plasma. Using the 10 TW laser, the physics of self-guiding and the limitations in regards to pump depletion over cm-scale plasmas were demonstrated. Furthermore, a novel injection mechanism was explored which allows injection by ionization at conditions necessary for generating electron energies greater than a GeV. The 10 TW results were followed by self-guiding at the 100 TW scale over cm plasma lengths. The energy of the self-injected electrons, at 3×10^{18} cm^{-3} plasma density, was limited by dephasing to 720 MeV. Implementation of ionization injection allowed extending the acceleration well beyond a centimeter and 1.4 GeV electrons were measured.

INTRODUCTION

Progress in laser wakefield accelerators (LWFA) has greatly benefited from the rapid development of short pulse, high power lasers. When first proposed in [1] the laser systems now in common use were not imagined. The striking feature of high energy gain, in very short distance, has always been noted, and while developments in laser technology continues, problems remain in order to make a practical accelerator device. First, in order to achieve the maximum energy gain, the laser must be guided over many Raleigh lengths. Second, a suitable injection scheme, which will produce a high quality electron beam, must be implemented. These topics are addressed here through self-guiding of the laser pulse and ionization injection of electrons.

THE BLOW OUT REGIME DEFINED

After experimental demonstration of the LWFA process in three Nature papers [2, 3, 4] W. Lu et. al. [5]described the blow out regime where the theoretical scaling for the self-guiding of short laser pulses in an underdense plasma, and the energy gain of self–trapped electrons is presented. The blow out regime describes the propagation of a short laser pulse travelling in underdense plasmas where the 3D radiation pressure causes complete electron cavitation. For the 3D model it can be shown that when $a_0 > 2$ the relative electron density is dn/n=1. The normalized vector potential is

$$a_0 = \frac{eE_0}{mc\omega_0} = 8.6\times 10^{-10}\sqrt{I\left(\frac{w}{\mathrm{cm}^2}\right)}\lambda(\mu\mathrm{m}).$$

For the "matched" spot size condition, $k_p w_0 = 2\sqrt{a_0}$, the laser pulse creates a stable self–guided wake structure with a spherical shape with radius R_b. Based on the idea of a spherical wake structure, the fields in r and z can be derived. Reference [5] gives the theoretical pump depletion length based on pulse etching due to local pump depletion and the de-phasing length based on the nonlinear group velocity of the laser. Finally an equation for maximum energy gain in the blow-out regime is derived. A 3D trapping theory and a derivation of wake potential as a function of a_0 is derived in [6,7]. These theoretical scaling equations are discussed below as they apply to recent experiments. For a tutorial on LWFA's see W. Mori in these proceedings.

Listed below are the pertinent formulas for LWFA in the blow out regime [5]. The matched spot size, given above, can be expressed as,

$$k_p w_0 = 2\sqrt{2}(P/P_c)^{1/6} \qquad (1)$$

where $P_c = 17\omega_0^2/\omega_p^2$ is the critical power in GW for relativistic self-focusing. The pump depletion length is,

$$L_{pd} = (\omega_0^2/\omega_p^2)c\tau \qquad (2)$$

The on axis longitudinal electric field is,

$$E(z) = E_{\max}\left(z/R_b\right) \qquad (3)$$

The normalized maximum electric field is

$$\frac{eE_{\max}}{mc\omega_p} = \sqrt{a_0} \qquad (4)$$

The dephasing length is

$$L_d = \frac{2}{3}\frac{\omega_0^2}{\omega_p^2}R_b = \frac{4}{3}\frac{\omega_0^2}{\omega_p^2}\frac{1}{k_p}\sqrt{a_0} \qquad (5)$$

The maximum energy gain is

$$\Delta W = \frac{2}{3} \frac{\omega_0^2}{\omega_p^2} a_0 mc^2 \qquad (6)$$

This can be written in terms of matched laser power as

$$\Delta W = \frac{4}{3} \frac{\omega_0^2}{\omega_p^2} (P/P_c)^{1/3} mc^2 \qquad (7)$$

TESTING SELF-GUIDING AND PUMP DEPLETION

With the UCLA Ti:Sapphire laser we wanted to begin an experimental investigation of the blow out regime. However, testing energy gain scaling with a TW scale laser seemed doubtful, because the electron energy gain scales with laser power to the 1/3. However, a second look at W. Lu's paper showed that an experimental study of self-guiding and pump depletion could be done. Fortunately, for $a_0 > 2$, and $P/P_c > 1$, the pump depletion length, Eq. 2 does not depend directly on laser power. The matching Eq. 1, has weak dependence on laser power so long as $P/P_c > 1$.

A series of experiments was performed that showed remarkable agreement with Eq. 1 and the pump depletion length Eq. 2. The results were obtained by imaging the self-guided laser spot at the exit of several different gas jet lengths. The results are published in [6] and reproduced here in Figure 1. Figure 1 shows the range of densities where guiding was observed in good agreement with Eq. 1 and Eq. 2. For each gas jet or cell length there is a minimum density and P/Pc where self-guiding was observed i.e. P/Pc > 1. Also, poor self-guiding was observed when the density was too low for the incoming laser spot size. In this case the laser was not well coupled to the plasma and did not create a sufficient self-guiding structure. If the plasma density was too high the self-guiding distance was limited by pump depletion in agreement with Eq. 2.

Similar results were obtained at the 100 TW scale using LLNL's Callisto Laser. With a much higher power laser we were able to significantly lower the plasma density and self-guide through a 1.4 cm long helium filled gas cell [8, 12]. The data for that result is included in Figure 1.

Perhaps the most essential feature for successful LWFA experiments is to have the right focusing condition for best possible laser coupling to the wake. The one knob in the parametric scans we have not explored is the scaling with laser spot size. In most cases if the laser is launched into the plasma near the correct spot size the pulse will eventually evolve into a stable self-guided equilibrium. To assure proper self-guiding and good coupling of the laser to the wake we measure the laser exit spot on each laser shot.
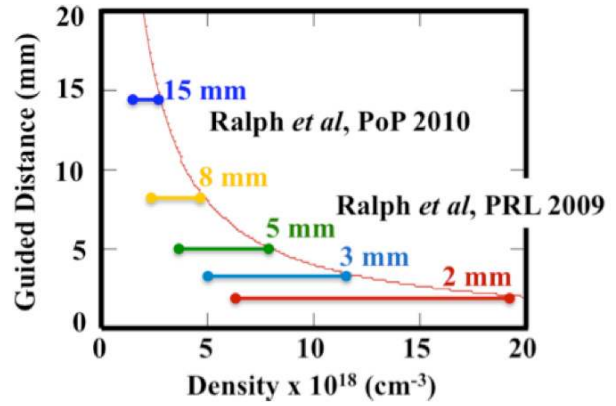

Figure 1: Maximum observed guiding distance verses plasma density. The data points refer to the discrete plasma lengths used and the range of plasma densities where self-guiding was observed. The theory curve shows the nonlinear pump depletion length based on etching due to local pump depletion for a 50 fs laser pulse.

TESTING THE MAXIMUM ENERGY GAIN FORMULA IN THE BLOW OUT REGIME

Comparing the maximum energy gain Eq. 6, to experimental measurements is difficult when relying on self-trapping for the electron source. For fixed laser power, we would like to lower the plasma density in order to reach the highest possible energy gain, but to reliably self-trap electrons, $P/P_c > 4$. Also, in our experiments, the wake needs some distance to evolve before trapping occurs [7]. Imperfect beam spot size matching and non-gaussian transverse laser profiles reduce the coupled power and so finding exact agreement with laser power and the energy gain equation is difficult.

Measurement of the energy gain scaling was performed at LLNL and considering the above gave good results. The estimated coupled laser power was 65 TW. As the plasma density was lowered, the gas jet length was changed in accordance with changes in the dephasing length. The highest measured energy was 720 MeV at 3×10^{18} cm^{-3}. The results are shown in Figure 2. These results give good agreement with Eq. 6, when wake evolution and trapping distance are taken into account. At the lowest density, PIC simulations show that after 2.5 mm of laser propagation, electrons begin to be self-injected.
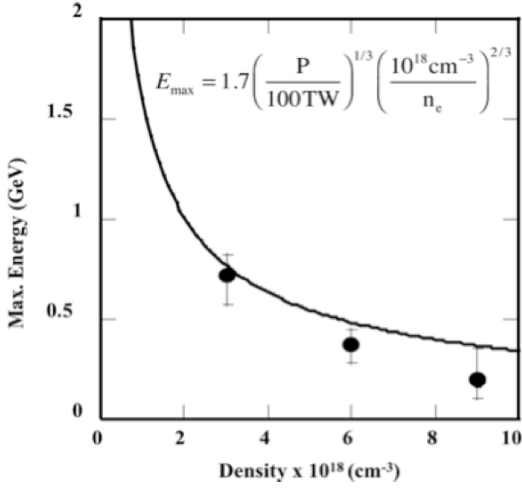
Figure 2: Measured electron energy verses plasma density. The theory curve is for 65 TW of laser power. Data taken from Ref. [7, 8]

SELF-INJECTION VS IONIZATION INJECTION

Most LWFA experiments rely on self-injection for a source of electrons. Near the dephasing length, these electrons tend to rotate in z, p_z phase space, which creates a narrow energy spread feature, often referred as mono-energetic.

In most cases it is very difficult to obtain useful electron beams by self-injection unless $P/P_c > 4$ or $a_0 > 3$. To achieve high energies requires high P_c and therefore high laser power. For example, to achieve 1 GeV with a 50 TW laser requires a plasma density of 1.5×10^{18} cm^{-3}. Subsequently $P/P_c = 2.6$ which is below threshold for self-injection, but not for ionization injection. The advantage of ionization injection over self-injection is it allows the LWFA to be operated at lower density and therefore reach higher electron energies. Again the method was studied in detail at UCLA [9] before being implemented at LLNL.

IONIZATION INJECTION THEORY

Electrons can be injected into a fully formed wake by ionization-injection. Ionization injection relies on the large difference in the ionization potential between successive ionization states of trace atoms in the plasma. For example, electrons from the K shell of nitrogen can be tunnel ionized near the peak of the laser pulse where the phase is favorable for trapping into the wake. The model used for the tunnel ionization threshold comes from ADK theory [11].

An electron is said to be trapped, when it gains enough energy to move at the phase velocity of the wake, v_p. A trapping condition can be derived based on how large a wake potential difference is required for the electron to gain enough energy to move at v_p. In [9] a full 3D analytic formula for the trapping condition was derived. The normalized potential difference required for trapping is given by,

$$\Delta\Psi = \sqrt{1 + p_{\perp f}^2} / \gamma_\Phi - 1 \qquad (8)$$

where $p_{\perp f}$ is the final normalized perpendicular momentum of the electron from the transverse wake fields and the residual momentum gain from tunnel ionization. As shown in [10] the trapping condition for an on axis electron, which is trapped at a location that does not overlap the laser field, is,

$$\Delta\Psi = \sqrt{1 + a_{0i}^2} / \gamma_\Phi - 1 \qquad (9)$$

where a_{oi} is the instantaneous normalized vector potential when ionization occurs. The electron cannot gain net momentum from the laser without some symmetry breaking of the field. The amount of momentum gained depends on the ionization phase of the field. Any amount of longitudinal momentum gained from the laser will reduce the required potential for trapping. In [10] an estimate of the 1D potential difference seen by an electron that is injected on axis is given by,

$$\Delta\Psi = -\int_{z_i}^{z_f} E_{max}(z / R_b)\,dz \qquad (10)$$

where, z_i and z_f are the longitudinal locations where the electron is injected and trapped are shown in Figure 3. As shown in Figure 3, electrons injected closer to $z = 0$ see a larger potential difference and are more easily trapped than those injected at $\Psi = 0$. From [10], the normalized vector potential can be expressed as function of a_0 as,

$$\Delta\Psi = -a_0(1 - z_i^2 / R_b^2) \qquad (11)$$

Ideally an electron born at $z = 0$ would be easiest to trap. However, the peak of the laser field is normally located at between $R_b/2$ and $3/4R_b$. Therefore, Eq. 11, gives the realistic value of a_0 for trapping to be from 1.3 to 2.3.
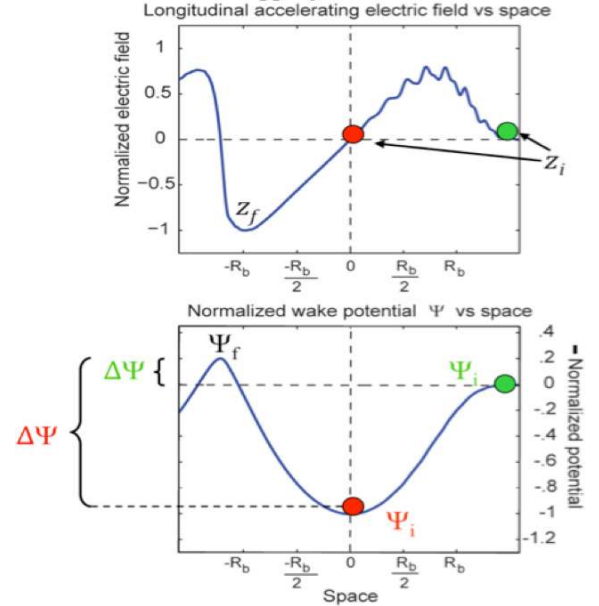

Figure 3: On axis line outs of longitudinal electric field and the wake potential verses z location in units of R_b for 2D OSIRIS simulation with $n_e = 1.4 \times 10^{19}$ cm^{-3}, $a_0 = 2.5$. The figure illustrates how ionization trapping increases the potential seen by the electrons (shown in red and green) when born closer $z = 0$. Ref. [10].

IONIZATION INJECTION USING THE 10 TW LASER SYSTEM AT UCLA

As shown in [9], we observed ionization trapping in nitrogen for a_0 between 1.6 and 2.5. These values correspond to the ionization threshold for N^{6+} and N^{+7}, and show good agreement with how trapping scales with a_0. We looked for trapping with a_0 less than 1 by using argon because the a_0 required to ionize the L shell of argon is lower than nitrogen. At best we were able to observe trapping at $a_0 = 1.4$, thus verifying that ionization trapping is limited by Eq. 11 and not by the ionization threshold of the trace impurity.

IONIZATION INJECTION USING THE CALLISTO LASER AT LLNL

Ionization injection was used to full effect with the Callisto laser at LLNL [12]. There we achieved electron energies up to 1.4 GeV. By using ionization injection, we were able to significantly reduce the plasma density from the self-injection result [7] and thereby obtain very high-energy electrons. The density was 1.3×10^{18} cm^{-3} and the estimated coupled laser power was ~110 TW. For these experiments, helium was used to produce a very homogeneous plasma, in a 1.4 cm long gas cell. CO_2 was used as the trace impurity gas because O^{7+} and O^{8+} have an ionization threshold of $a_0 \simeq 3$, which is consistent with the matched spot size condition. Similar to the results obtained at UCLA, the electron spectra had a continuous energy spread. Methods to reduce the energy spread are discussed next.
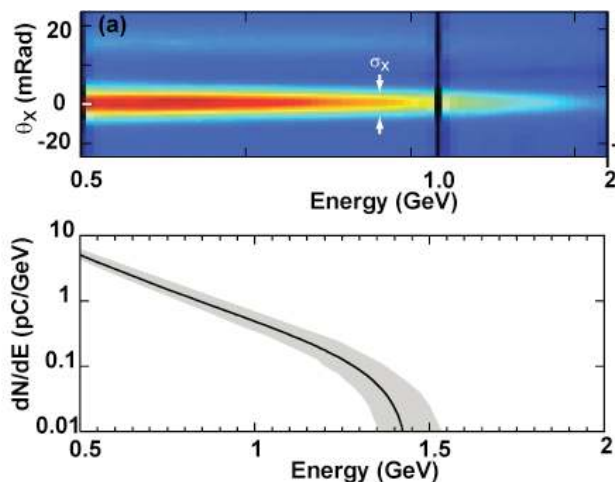

Figure 4: Raw electron data from the image plate spectrometer and the de-convolved electron spectrum for the ionization injection experiment with the Callisto Laser.

REDUCING THE ENERGY SPREAD FROM IONIZATION INJECTION

To reduce the energy spread, a method to turn off injection or reduce the distance where injection occurs is needed. In an experiment where weak self-guiding occurs, the peak laser electric field will be reduced as the laser propagates and will quickly fall below the K and L shell ionization threshold, thus turning off injection. Using a circularly polarized laser can reduce the ionizing electric field without changing intensity. For the same laser fluence circular polarization will not change the laser intensity, but will reduce the peak electric field by $\sqrt{2}$. This will shift the ionization phase closer to the peak intensity of the laser.

In a proof of principle experiment at UCLA, the combination weak self-guiding and circular polarization was shown to produce more narrow energy spread electron beams than with linear polarization.

For similar experimental parameters, Figure 5 compares the measured electron spectra for a linear and a circular polarized laser. The narrower spectrum when using a circular polarized laser demonstrates the effect. In order to verify and improve the method, 2D OSIRIS simulations were used.

The simulation results compare the electron spectra for 7.5 TW linear and circular polarized lasers in a 3 mm long helium plasma with a 5% nitrogen impurity. The density was 5.85×10^{18} cm^{-3} and $P/P_c = 1.5$. For the circular polarized case the peak $a_0 = 1.6$. Injection occurs and then immediately stops when the laser electric field falls below the ionization threshold. Acceleration continues up to 225 MeV with a 3% energy spread is shown in Figure 6. For the linear polarized case, the peak $a_0 = 2.3$ and the electron spectra has a broad energy spread typical of continuous ionization injection of electrons.
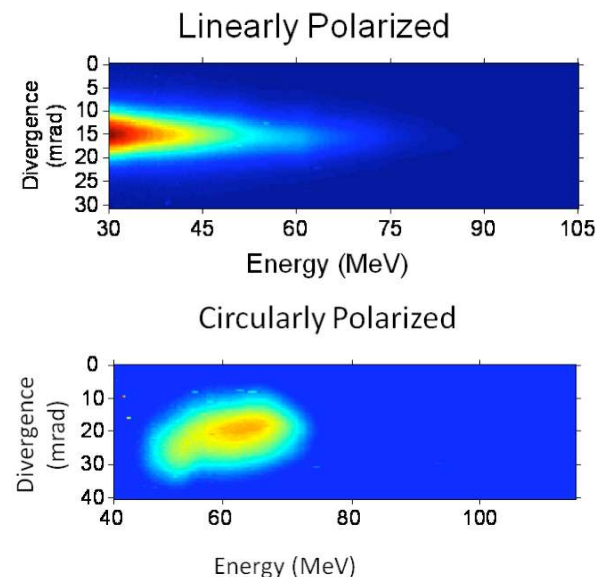

Figure 5: Comparison of measured electron spectra for linear and circular polarized laser
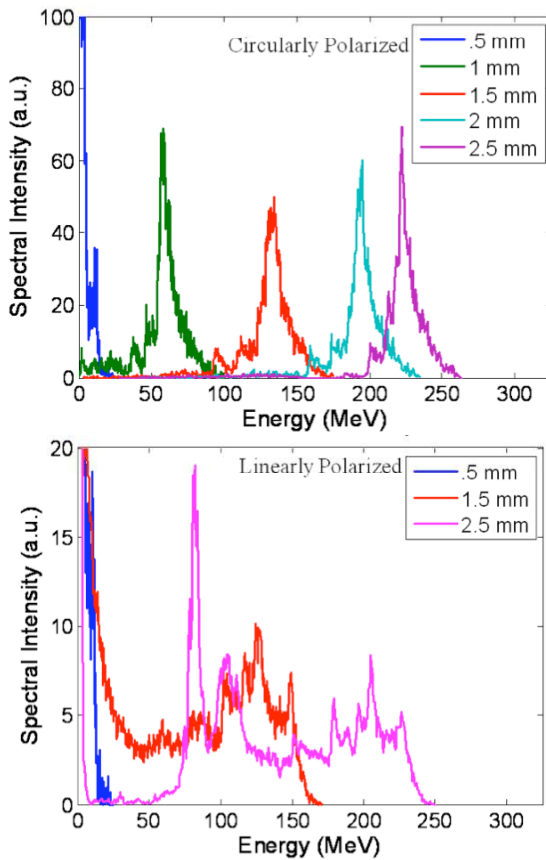
Figure 6: 2D OSIRIS simulation results comparing the accelerated electron spectra with circular polarization and with linear polarization. With circular polarization injection is turned off early in the simulation when the electric field falls below the ionization threshold. In the linear case ionization injection continues throughout the simulation resulting in a large energy spread.

STAGED INJECTION AT LLNL

A staged injection plan is illustrated in Figure 7. The idea is to have two stage set up where in the first cell a beam of electrons is created by ionization injection. The second stage does not contain any trace impurity and acts a LWFA below threshold for self-injection. A 2D OSIRIS simulation demonstrates the concept and the simulation result show a beam reaching 1.5 GeV with a narrow 1% energy spread. The results of staged injection experiments and 3D simulations are presented at this conference.
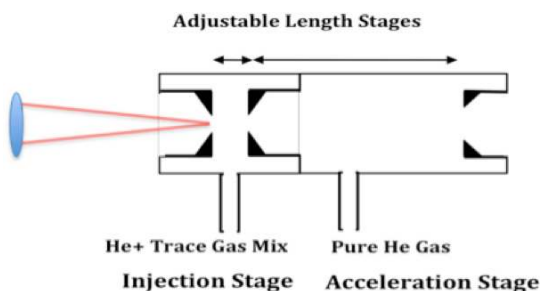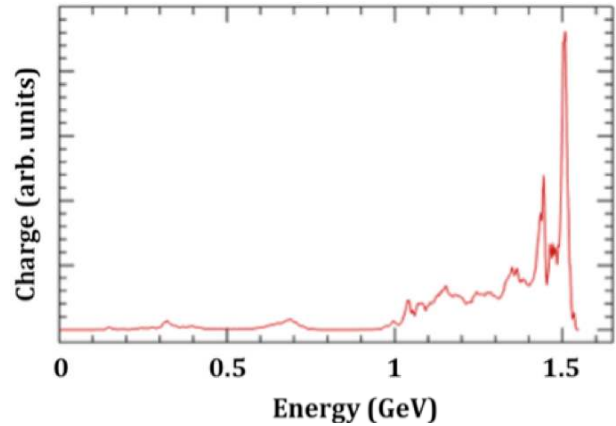

Figure 7: Illustration of staged injection concept.

Figure 8: The electron energy spectrum from a 2D OSIRIS simulation for a 100 TW LWFA with staged injection in 1.5×10^{18} cm^{-3} density plasma

CONCLUSION

We have been able to test and developed our experimental ideas on a small scale platform at UCLA and take what we have learned to the Callisto Laser at LLNL. Results using the UCLA 10 TW laser were scaled to 100 TW experiments with great success. At UCLA, we verified scaling equation for self-guiding and worked out the ionization injection scheme. At LLNL, we were able to test how electron energy gain scales with plasma density, plasma length and laser power. When ionization injection was used, a continuous electron energy spectrum was measured with energy up to 1.5 GeV. Methods to reduce the electron energy spread were investigated and include a staged injection experiment at LLNL.

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