100 MeV Injector Cell for a Staged Laser Wakefield Accelerator

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Abstract. A 100 MeV electron laser wakefield injector based on a sub-millimeter gas cell is presented. The gas cell, used mainly to overcome the density inhomogeneity associated with gas jets, is capable of yielding a homogeneous plasma source with densities less than $2 \times 10^{19}$ cm$^{-3}$. Sharp step plasma density boundaries were obtained by using the laser to drill the gas cell pinholes as small as 100 µm in diameter. The gas cell lengths were comparable to the dephasing length. The gas cell length and density were varied to study electron bunch characteristics. The UCLA 10 TW Ti:Sapphire laser was focused into the gas cell where helium and hydrogen were used as target gases with a few percent nitrogen impurity added to induce ionization trapping of the electrons [1]. The observed electron beams had divergences less than 2 mR. A model for producing low divergence beams is presented.

Keywords: Laser Wakefield Acceleration; Density Ramps; Electron Beam Divergence
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INTRODUCTION

In order to experimentally verify nonlinear laser wakefield theory and to study its scalings, a gas cell was developed with carefully controllable length that can be adjusted to the dephasing length (as low as 350 µm in this experimental work). If the dephasing is controlled, it becomes possible to answer questions such as whether the maximum energy gain of an electron bunch is consistent with nonlinear wakefield theory and whether dephasing leads to energy spread within an electron bunch. This paper describes the gas cell designed for the purpose of experimentally verifying nonlinear laser wakefield theory, the experimental results from the characterization of the gas cell, and the low-divergence electron beams produced, and it gives a possible explanation of how density ramps can be used to control the divergence of electron beams produced using laser wakefield acceleration (LWFA).

DEVELOPMENT OF GAS CELL

The motivation for the development of the gas cell was to precisely control the length of the plasma so that the electron acceleration length could be adjusted to be less than, equal to, or greater than the dephasing length. If this can be demonstrated, it will be possible to use the gas cell to create electron beams with prescribed energy and energy spread for injection into a staged LWFA. The gas cell designed for this experiment (shown in Figure 1) provides a flexible experimental platform for the study of LWFA-produced electron beams. The key feature of the gas cell is its variable length that allows the gas cell to have a length equal to the dephasing length. The laser-drilled entrance and exit pinholes of the gas cell permit self-alignment with the laser used for LWFA. Laser drilling also offers flexibility in the size of the pinholes; very small pinholes will result in density ramps that are short, and large pinholes provide longer density ramps. The plasma density in the gas cell scales linearly with the backing pressure, and the cell can support a wide range of plasma densities ($2 \times 10^{19}$ cm$^{-3}$ and below). The produced plasma is stationary, uniform, and reproducible in the interaction region. Examples of the plasma electron density profiles obtained using interferometry for three different conditions are shown in Figure 2. From these profiles, one can see that the electron density can be made to be fairly uniform within a measurement accuracy of ± 20%.
FIGURE 1. (a) Photograph of gas cell. (b) Schematic of cut-away of gas cell.

FIGURE 2. Plasma density profiles for 3 different shots. Red curve is density on axis. Green and magenta curves are average densities 8 µm off axis (above and below, respectively).

EXPERIMENTAL RESULTS FROM GAS CELL CHARACTERIZATION

The gas cell was used to determine whether the produced electron beams were consistent with expectations from nonlinear wakefield theory. The 10 TW Ti:Sapphire laser at UCLA, with a central wavelength of 815 nm and a 40-50 fs pulse width, was used to produce wakes in the gas cell. The laser pulses were focused to a 6 µm spot at the entrance hole of the gas cell using a f6 off-axis parabola configuration. The mixtures of 95% helium with 5% nitrogen and 90% hydrogen with 10% nitrogen were used to ensure electron trapping at the beginning of the cell without the need for laser evolution. The spot size was chosen to be approximately equal to the matched spot size to minimize the evolution of the laser pulse inside the plasma.

Using this setup, electron beams produced by the gas cell were recorded as the gas cell length was decreased from 1.2 mm to 350 µm for parameters where the dephasing lengths were between 500-350 µm. Electron beams were dispersed with a 0.9 T magnet with an effective length of 65 mm onto a scintillator placed 19 cm from the exit of the magnet. The laser light was dumped using a thin aluminum foil.

For cell lengths on the order of twice the dephasing length or greater, the electron energy spectrum is significantly modulated as shown in Figure 3(a). For cell lengths slightly beyond the dephasing length as shown in Figure 3(b), the electron bunch is relatively monoenergetic and has energies consistent with dephasing-length limited maximum energy gain which is given by [2]

$$E_{\text{max}}[\text{GeV}] = 1.7 \left( \frac{P[\text{TW}]}{100} \right)^{3} \left( \frac{10^{18}}{n_{a} \left[ \text{cm}^{-3} \right]} \right)^{2} \left( \frac{0.8}{\lambda_{0} [\text{µm}]} \right)^{4}$$

(1)

When the gas cell is slightly shorter than the dephasing length as shown in Figure 3(c), the maximum energy gain is less than the dephasing-length limited maximum energy gain, and a continuous charge distribution is visible.
The produced electron beams also exhibited very narrow divergence as shown in Figures 4 and 5. The electron spectra were imaged using two scintillators with different thicknesses. The thinner scintillator is a Saint Gobain BC-404 plastic scintillator and has a thickness of 1.5 mm. The thicker scintillator is a Saint Gobain BC-400 plastic scintillator and has a thickness of 5 mm. With the 5 mm BC-400 scintillator, the electron beams had a minimum dispersed divergence of 2.6 mrad (Figure 4(a)) and a minimum undispersed divergence of 1.9 mrad (Figure 4(b)). However, when the 1.5 mm BC-404 scintillator replaced the 5 mm BC-400 scintillator, the observed divergence narrowed further as shown in Figure 5 and exhibited an “exponential” transverse profile that peaks at a single pixel as shown in Figure 6. Because a Gaussian cannot be fit to this “exponential” transverse profile, it is difficult to define the divergence of this beam. The observance of these “unresolvable” (less than a mrad) divergences leads to two questions. Why is the divergence so small? How can the narrow divergences be experimentally resolved?

**FIGURE 3.** Representative electron spectra for gas cell lengths (a) on the order of twice the dephasing length, (b) slightly longer than the dephasing length, and (c) slightly shorter than the dephasing length.

**FIGURE 4.** Electron spectra and transverse lineouts for (a) dispersed (2.6 mrad divergence) and (b) undispersed (1.9 mrad divergence) beam profiles using 5 mm BC-400 scintillator.
FIGURE 5. Electron spectra with 1.5 mm BC-404 scintillator. Transverse profiles are exponential and rise to a single pixel.

FIGURE 6. Attempt to fit Gaussian to exponential profile. Lack of good fit makes it difficult to determine divergence.

ORIGIN OF LOW DIVERGENCE

A potential answer to why such narrow divergences are observed may come from studying the properties of the density down ramp at the exit of the gas cell. To illustrate this concept, consider the betatron motion of a single electron trapped inside the wake. Since the trapped electron is moving at the phase velocity of the wake, the force that the trapped electron experiences is that due to an ion column. Therefore, the equation of motion of the electron in the wake is given by

\[ \frac{d^2r}{dz^2} + \frac{1}{\gamma} \frac{dr}{dz} \frac{d\gamma}{dz} + k_\beta^2 r = 0 \]  

(2)

where \( r \) is the amplitude of the oscillation (distance of electron from axis of ion column), and \( k_\beta \) is the betatron wavelength for an ion column \( k_\beta = \frac{\omega_p}{c \sqrt{2\gamma}} \). This equation of motion shows that the motion of the electron depends on three terms—\( \gamma \), \( \frac{d\gamma}{dz} \), and \( k_\beta \). If the electron is assumed to be of constant energy (\( \frac{d\gamma}{dz} = 0 \) making the second term in the equation of motion zero), then the amplitude of oscillation is larger for a higher energy electron (larger \( \gamma \)) and the divergence \( dr/dz \) is smaller for a higher energy electron. However, if the electron is being accelerated (as is the case in LWFA up to the point of dephasing), the \( \frac{1}{\gamma} \frac{dr}{dz} \frac{d\gamma}{dz} \) term dominates the increase in amplitude due to the increasing \( \gamma \) and therefore damps the oscillation. When the electron exits the plasma via a density down ramp, \( k_\beta \) will increase. This increase results in an increase in the oscillation amplitude and a further reduction in the divergence.
To illustrate these scalings, the analytical solutions to the equation of motion were found for three different density down ramps and plotted in Figure 7. For these solutions, the trapping energy of the electrons is 6.25 MeV (the energy at which the velocity of the electron equals the phase velocity of the wake), and electrons were assumed to be trapped 1 µm off axis. The first case modeled was a plasma with no exit ramp. The blue curve in Figure 7(a) is the trajectory of the electron, and the magenta curve is the density profile. This trajectory shows that as the electron is accelerated, the wavelength of its oscillation increases and the amplitude of the oscillation decreases. When the electron exits the plasma, it no longer executes harmonic motion and so will continue to travel with the properties it had when exiting the plasma. The blue curve in Figure 7(d) is the divergence of the electron and shows that accelerating the electron decreases its divergence. However, in this case, there is no exit density down ramp, so the divergence of the electron as it exits the plasma will depend on the phase of its oscillation as shown in Figure 7(g).

**FIGURE 7.** Analytical solutions for trajectory and divergence of electron in a wake for different down ramps. (a) and (d) are trajectory and divergence, respectively, for no exit ramp. Resulting electron divergence is 12.82 mrad. (b) and (e) are trajectory and divergence, respectively for a 23.5 µm HWHM Gaussian ramp. Resulting electron divergence is 6.61 mrad. (c) and (f) are the trajectory and divergence, respectively, for a 235 µm HWHM Gaussian ramp. Resulting electron divergence is 1.21 mrad. (g), (h), and (i) are electron divergence for six different trapping phases. Long density ramp shows narrower divergences over a wide range of trapping phases.
The second case modeled is a short density down ramp (assumed to have a Gaussian shape with a half-width half-max (HWHM) of 23.5 µm). The blue curve in Figure 7(b) is the trajectory of the electron, and the magenta curve is the density profile. As in the case with no exit ramp, the wavelength of the electron’s oscillation increases and the amplitude decreases as the electron accelerates. The blue curve in Figure 7(e) shows the electron’s divergence for this case. Here, as the electron passes through the down ramp, the presence of the ramp increases $k_\beta$ which narrows the divergence of the electron so that when it exits the plasma, its divergence is less than the first case. Figure 7(h) is the divergence of the electron for six different injection phases. Like the case of no exit ramp, the exiting divergence for the short exit ramp is strongly dependent on trapping phase.

The third case modeled is a long density down ramp (assumed to have a Gaussian shape with a HWHM of 235 µm). The blue curve in Figure 7(c) is the trajectory of the electron, and the magenta curve is the density profile. With the long density down ramp, the increase in $k_\beta$ causes an increase in the amplitude and wavelength of the oscillation. However, as shown in Figure 7(f), the electron divergence is greatly reduced through the down ramp so that divergence is extremely small regardless of the phase at which the electron exits as shown in Figure 7(i). Thus, the presence of a density down ramp is potentially the physical reason behind the narrow divergence electron beams seen in experiments.

CONCLUSION

At UCLA, a gas cell ideal for studying the dephasing-length limited properties of nonlinear laser wakefield theory was developed. Using this gas cell, electron bunches with maximum energy gain consistent with the dephasing-length limited energy gain and monoenergetic electron bunches were demonstrated. Further, the presence of density down ramps was explored as a possible explanation of the production of electron beams with extremely small divergence. Therefore, in the future, control of down ramps could potentially enable tuning of the divergence of electron beams.

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