

ELECTRON ACCELERATION EXPERIMENTS USING THE HERCULES LASER SYSTEM AT THE UNIVERSITY OF MICHIGAN*

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Abstract

The HERCULES laser system at the Center for Ultrafast Optical Science at the University of Michigan has been used to generate GeV range electron beams using Laser Wakefield Acceleration (LWFA). The electron beam quality is shown to be improved substantially using gas mixtures - causing an increase in beam charge and a potential decrease in emittance. The dynamics of the acceleration process can also be determined by measurements of spatially resolved scattered laser radiation and the use of femtosecond optical probing techniques.

INTRODUCTION

In a laser wakefield accelerator, an intense ultra-short laser pulse generates a plasma wave, known as a wakefield, with a phase velocity close to the speed of light. A relativistic electron beam co-propagating with the wakefield can therefore remain in an accelerating phase of the wave for a relatively long distance, and gain energy from its longitudinal electric field. Plasma waves can support electric fields orders of magnitude stronger than those in radio-frequency cavities, and hence may provide a compact alternative, or complement, to conventional electron accelerators in the future.

In the strongly nonlinear regime, the laser pulse expels electrons from its focal volume but has a negligible effect on the ions, which remain, resulting in a cavity with strong electromagnetic fields. Electrons from the periphery of the cavity are pulled inwards by the strong Coulomb attraction and form a thin high-density sheath around an approximately spherical "bubble" [1-2]. This bubble has ideal accelerating and focusing properties for electrons within the cavity, and at the point where the sheaths cross at the rear of the bubble, the field is particularly strong. Here, electrons can be accelerated to the phase velocity of the bubble in a time shorter than their crossing time and are therefore trapped. Under certain conditions, the trapped electron beam can have a quasi-monoenergetic energy distribution.

Control of the onset of this self-trapping is not independent of the accelerated electron beam charge, peak energy and emittance, as all of these depend on the drive laser pulse characteristics and global plasma density.

Initiating trapping independently of the acceleration process can be performed by implementing an external injection source of electrons or using an additional laser pulse to cause injection. This second laser

pulse can be used to ionize electrons within the wake to initiate trapping. A related ionization trapping mechanism has been demonstrated in electron beam driven plasma wave accelerator experiments on the Stanford Linear Collider (SLAC) [3]. Ionization induced trapping was inferred in experiments on laser wakefield acceleration in a capillary due to relatively high Z ions from the walls migrating to the laser axis [4].

The self-trapping condition is that an electron gains sufficient forward momentum from the longitudinal electric field to reach the phase velocity of the bubble before it slips out of the accelerating phase. Creation of free electrons by ionization, initially at rest within the electron cavity, can initiate trapping because these electrons experience additional energy gain due to the net potential difference between the edge of the bubble and its interior. This translates to a lowered trapping threshold, and is maximized if the electrons are created at the minimum of the potential.

Presented here is an experimental demonstration of electron trapping initiated by ionization in a laser wakefield accelerator. We show that this mechanism increases the trapped charge by up to an order of magnitude and potentially decreases the emittance of the electron beam generated. A range of noble gases, and nitrogen, is systematically added as a small percentage to helium gas prior to plasma formation. It is determined that optical field ionization of inner shell electrons of the higher Z gas plays an important role in determining the amount of trapped charge. Although there is a small increase in overall electron number density due to the higher Z gas additive, it is shown to be insufficient to account for the increase in charge in the trapped electron bunch. In addition, the behavior of the trapping is consistent with the field-ionization thresholds for the various gas species). added to the helium. Improvements in beam charge and emittance are important for applications such as x-ray generation through inverse Compton scattering, or free electron lasers, as well as x-ray generation by oscillation in a plasma based wiggler. By using a gas mixture, lower power laser systems can potentially be used to generate higher charge, higher energy, and decreased emittance monoenergetic electron beams than can be produced using a fully pre-ionized plasma.

EXPERIMENT

In these experiments, pulses from the HERCULES laser system [5] at the University of Michigan (30 fs, 800 nm Ti:sapphire) were focused using

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an $f=10$ off-axis parabolic mirror onto the edge of gas flow from a 3 mm diameter conical supersonic nozzle. The laser wavefront was corrected with a deformable mirror, yielding a focused spot of 10 μm full-width-half-maximum (FWHM). The experiments were conducted using a laser peak power ranging from 24-120 TW on target. The focused peak intensity was $I = 3.5 \times 10^{19}$ at 30 TW and $I = 1.5 \times 10^{20}$ at 120 TW. Diagnostics in the forward direction included an electron spectrometer (0.8 T permanent magnet, Lanex phosphor screen, and Charged Coupled Device) with electron energy detection range of 47-800 MeV, transmitted laser mode imaging, and transmitted laser spectrum. A transverse probe beam was used for interferometry. Sidescattered light from the plasma was split with a wedge and sent to an imaging CCD as well as a spectrometer with 260 nm spectral window centered around the laser wavelength. Gas was pulsed from a solenoid valve (5 ms opening time) through the gas nozzle. Gases added to the helium target included air, nitrogen, neon, argon, krypton, and xenon. To ensure a homogeneous mixture, the gases were agitated in a 2.5 liter steel vessel. The vessel and all gas lines were evacuated before introducing any gases. Care was taken to eliminate leaks in the lines. In order to accurately produce low additive to helium ratio mixtures, the gas additive was introduced using a low pressure regulator (typically < 4 atm) first, and subsequently helium was added at high pressure (67 atm) from an isolated supply. A third regulator was installed on the output of the mixing vessel, maintaining constant pressure for many tens of shots with the same gas mixture. Before a typical experimental run, air contaminant can be introduced into the gas as a result of changing regulators or gas bottles.

However for these experiments many gases were installed on a manifold so that air would not be introduced when changing gases. A density scan was conducted with each gas mixture ratio for a number of different ratios of additive to helium, between 0.1 and 5.95 by partial pressure. Electron number density was monitored via both transverse interferometry and Raman-shifted scattered light. Electron plasma densities in the range $5 \times 10^{18} - 3 \times 10^{19} \text{ cm}^{-3}$ were investigated.

Certain gas mixtures significantly improved the probability of injecting electrons and also increased the amount of charge in the electron beam relative to pure helium.

However, it is important to accurately diagnose the exact electron number density in the interaction with the higher Z additive. Strong sidescatter was always emitted only throughout the first 400-500 μm (approximately one Rayleigh range) of the plasma. With higher power shots (> 100 TW) sidescatter was emitted further into the plasma. The wavelength of the scattered light was observed to be shifted to the red of the initial laser wavelength, (i.e. stimulated Raman side scattering). The gas mixture ratios are defined by the absolute pressure of the gas additive relative to the absolute pressure of helium. For each 1% increase in additive mixture of a gas with n electrons which can be ionized the

electron density will increase by $(n \sim 2)\%$ relative to helium gas at the same pressure. The electron density was also independently confirmed by simultaneous interferometry of the channel. The effect of gas additives on beam charge is shown in Fig. 1. In shots using 30 TW laser power, a nitrogen additive consistently led to an increase in the total integrated charge of almost an order of magnitude compared to a pure He target with equal electron density, Fig. 1a.

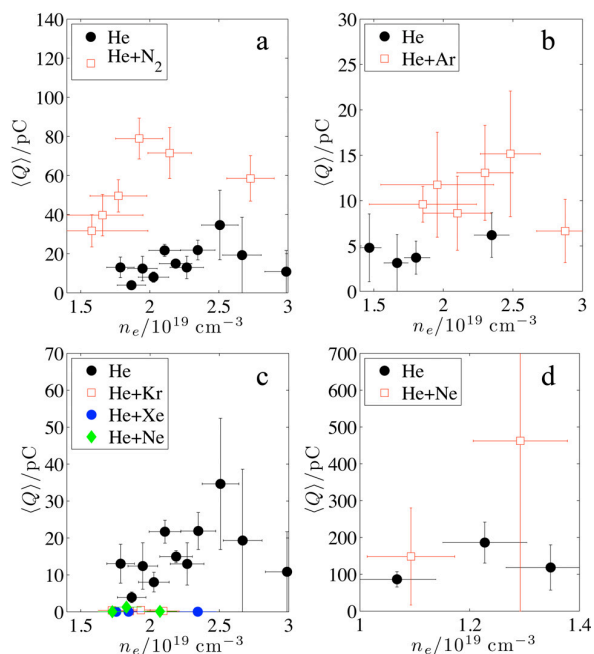


Figure 1: Integrated charge above 30 MeV measured by the electron spectrometer as a function of electron number density. The values represent an average of 5-20 shots for which electron signal is clearly above background. For gas mixtures the electron density increase is due to a change in the proportion of additive to helium held at constant neutral gas density, for pure helium the electron density increase is due to an increase in neutral gas density. The experiments were performed with a laser power of (a) 30 TW, (b) 24 TW, (c) 30 TW and (d) 120 TW.

Using a slightly lower power of 24 TW, argon also showed a substantial charge increase, Fig. 1b. Neon and other higher Z gas additives consistently decreased the beam charge in all cases at 30 TW, Fig. 1c. At 120 TW, using neon, an improvement in the mean trapped charge compared with helium was recorded, Fig. 1d. More interestingly, this behavior was significantly different from the 30 TW case, Fig. 1c.

These results can be understood by consideration of the optical field ionization thresholds for the different species. Both nitrogen and argon have a number of L-shell or M-shell electrons with a field ionization intensity threshold of $\text{IBS} < 10^{17} \text{ Wcm}^{-2}$, and can be considered pre-ionized before the formation of the bubble.

However, the K-shell electrons for nitrogen have a threshold intensity for ionization of $\text{IBS} \sim 10^{19} \text{ Wcm}^{-2}$, and so the majority will be freed near the peak of the

pulse. Likewise, the L-shell of argon has eight electrons with ionization threshold intensities ranging from 10^{18} to 10^{19} Wcm^{-2} , and so a proportion of the electrons are expected to be freed near the peak of the pulse. Xenon and krypton have large numbers of outer shell electrons at low ionization thresholds that presumably cause ionization defocusing of the pulse and prevent stable wakefield formation, which could be observed in interferometry images. Krypton has almost double the number of electrons that argon has, below an ionization threshold of $\text{IBS} < 10^{18}$ Wcm^{-2} . Neon has an L-shell which is fully ionized below an ionization threshold of $\text{IBS} < 10^{17}$ Wcm^{-2} , but its K-shell is ionized at close to $\text{IBS} \sim 10^{20}$ Wcm^{-2} , which is significantly higher than the peak intensity of the laser at 30 TW. This explains the different behavior of neon additives at 120 TW vs. 30 TW. The intensity and species dependent increase in charge is a strong indication of an ionization trapping mechanism.

Adding too much higher Z gas, of any species, was also found to be detrimental to electron injection, also due to ionization defocusing (for example, Fig. 1b, far right). The balance of ionization seeded injection and ionization defocusing creates a window of gas additive mixture ratios over which electron injection is enhanced. The mixing chamber apparatus allowed for systematic control necessary for this study. However, by merely exposing the gas lines to a small quantity of air before filling with helium, results similar to the nitrogen additive run were achieved.

Electron spectra were also obtained during the experiment. It was clearly demonstrated that the increase in charge is not at the expense of mean energy, for otherwise identical conditions and it was also shown that quasimonoenergetic electron spectra could be obtained with argon and neon additives respectively. The mean energy for the electron beam produced by ionization trapping was measured to differ by a statistically insignificant amount from those produced by self-trapping in helium only. This is to be expected, as ionization should not significantly modify the bubble structure due to the bulk of electrons being pre-ionized in all cases studied.

A measurement of beam divergence was taken by imaging a Lanex screen placed 1 m behind the target with the magnet removed. Typical profiles are shown in Fig. 2. The mean divergence in the vertical direction was about 5 mrad, averaged over 5 shots for the case of pure helium and about 3 mrad averaged over 8 shots for He +

1% Ar. The integrated charge from the shots with Ar additive was, on average, twice that of shots with pure He. There is also a clear qualitative difference between the profiles in the two cases. Although not a measure of the transverse emittance of the beam, it can be inferred that the increased collimation of the beam corresponds to an improved emittance, if a comparable source size is assumed.

In conclusion, ionization induced trapping in a laser driven wakefield accelerator has been investigated by exploring the parameter space of atomic number and impurity concentration. The addition of a higher Z additive has been shown to increase the trapped charge and lower the transverse emittance of the generated electron beam as compared to pure helium at the same electron density. This should be a useful trapping mechanism for efficiently producing electron beams where stringent constraints on the beam emittance and charge are required such as x-ray production in a plasma or conventional wiggler, as well as to control the injection mechanism.

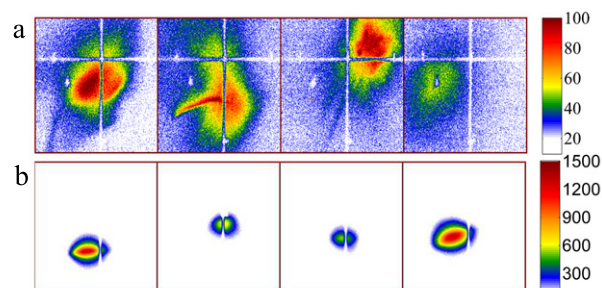


Figure 2: Electron beam profiles measured on a Lanex screen 1 m from the target. The top four images, (a), are from shots with pure helium and the bottom four, (b), are from shots with a 1% argon additive, both at equal electron number density $n_e = 2 \times 10^{19}$ cm^{-3} . Note the difference in color scale, which represents electron signal [arb] per pixel.

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