INVESTIGATION OF IONIZATION INDUCED TRAPPING IN A LASER WAKEFIELD ACCELERATOR

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Abstract

Controlling the trapping of electrons into laser generated plasma wakefields is an important step in obtaining a stable reproducible electron beam from a laser wakefield accelerator. Recent experiments at UCLA have focused on using the different ionization potentials of gases as a mechanism for controlling the trapping of electrons into an laser wakefield accelerator. The accelerating wakefield was produced using an ultra-intense ($I_o \sim 10^{19}$ W / cm^2), ultra-short ($\tau_{FWHM} \sim 45$ fs) laser pulses. The laser pulse was focused onto the edge of column of gas created by a gas jet. The gas was a mixture of helium and nitrogen. The rising edge of the laser pulse fully ionizes the helium atoms and the first five bound electrons of the nitrogen which are expelled by the laser to create a wake. Only at the peak of the laser pulse is it intense enough to ionize the most tightly bound electrons of nitrogen. These electrons are 'born' into a favorable phase space within the accelerating wakefield and are subsequently trapped and accelerated. The observed accelerated electrons were dispersed using a dipole magnet with a ∼ 1 Tesla magnetic field onto a phosphor screen.

INTRODUCTION

Several methods have been developed to accelerate electrons using intense laser pulses in plasmas. Common to all methods is the necessity to inject or trap electrons into the accelerating field of the wake excited in the plasma by the laser. There has been much effort in developing a method for the reliable and stable injection and acceleration of electrons in a laser wakefield accelerator. Previously, it has been reported by Oz. et al. [1], that in a electron beam driven wakefield accelerator, electrons can be trapped into a wakefield through ionization effects. In this paper, a new method of injecting electrons into a laser driven wakefield through ionization induced trapping, will be discussed and experimentally investigated. The principles behind ionization induced trapping in a laser wakefield accelerator are illustrated in figure 1. First, to create an accelerating structure, an ultra-short $\sim 45 fs$, ultra-intense $I_o \sim 10^{19}$ W / cm^2 laser pulse is focused onto a column of gas. The gas has several ionization states. The front edge of the laser pulse is sufficiently intense to ionize the most weakly bound electrons of the gas and create a plasma. The ponderomotive force of the laser then pushes these electrons around the pulse and sets up an electron plasma wave or wake. The heavier plasma ions remain essentially fixed on the timescale of few plasma periods. An electric field, with a component in the direction of laser propagation, is created due to the charge separation of the plasma electrons of the wake and the stationary ions. Only close to the peak of the laser pulse is it intense enough to ionize the most tightly bound electrons of the gas. These electrons are 'born' into the accelerating wake field created by the lower bound electrons of the gas. The wake and its electric field move with the laser through the plasma near the the group velocity of the laser, v_g. In order for electrons to gain energy and be accelerated by the electric field of the wake, they must stay phased with the field. The K-shell electrons of nitrogen that are ionized into the moving wakefield are initially at rest. Therefore, in the frame of the laser, these electrons slip back through the wake. As they slip back, they can gain energy from the potential created by the electric field of the wake. If they gain enough energy to be moving at v_g, then they will turn around and begin to move forward with respect to the wakefield and be accelerated to higher energies.

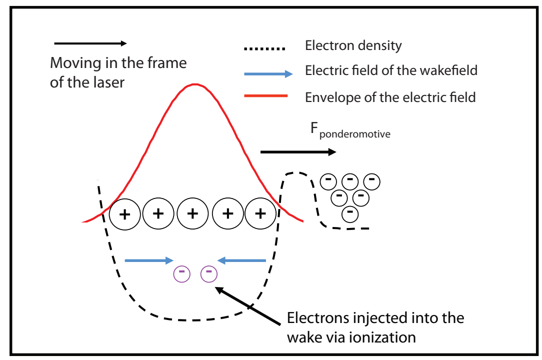

Figure 1: 1-D physical picture of ionization induced trapping in a laser driven wakefield accelerator

EXPERIMENT AND RESULTS

Experiments to investigate ionization induced trapping were conducted at UCLA using a Ti:Sapphire laser which can produce laser pulses with 200-400 mJ of energy with a pulse length of ∼ 45 fs (FWHM of the intensity). The laser was focused to a spot size w_o of 6 μm and reached peak intensities of $\sim 10^{19}$ W / cm^2. In these experiments, a mixture of helium and nitrogen gas was used. A mixture of helium and nitrogen gas rather than pure nitrogen was chosen to reduce the effect of laser prepulse on the experiment. The electrons from these gases were tunnel ionized and their ionization appearance intensities were calculated using the barrier suppression model [2]. In figure $2a$

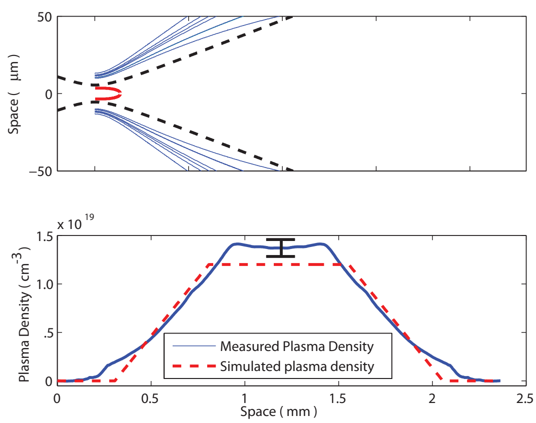

Figure 2: a) Dashed curve is the 1/e laser envelope, bold line is the ionization contour for the 6th state of N, thin lines are the ionization contours for He and the first 5 states of N for vacuum beam propagation. b) Solid line is the typical recovered plasma density of the HeN_2 mix. There is a 1 x 10^{18} cm^{-3} uncertainty in the measured density. The dashed line is the plasma density profile used for simulations.

the spatial contours of ionization intensity for different ionization states are plotted for an assumed bi-Gaussian laser pulse. The spot size, pulse width and energy of the theoretical Gaussian were chosen from the measured experimental parameters. As seen in figure $2a$, the dashed curve represents the $1/e$ amplitude of the electric field. The contours outside the $1/e$ amplitude are from the first 5 ionized states of nitrogen and the 2 states of helium. The only contour inside the $1/e$ amplitude comes from the 6th ionization state of nitrogen. This contour plot indicates that only close to the peak focused intensity is the laser intense enough to ionize the 6th state of nitrogen. For a laser pulse with 250 mJ of energy and a pulse width of 45 fs the ionization of the 6th state of nitrogen occurs over a radius of $\sim$ 3.5 μm and extends over a distance of $\sim$ 130 μm (1 Z_R). Note that the effects of relativistic self focusing and self-guiding [3] [4] will significantly modify the lasers divergence in the plasma. This will allow the intensity to stay above the threshold for ionizing nitrogen 6 over a longer distance than the vacuum laser contour.

Figure 3 shows the ionization appearance intensity for nitrogen and helium vs time, assuming an intensity profile given by a Gaussian laser pulse with an I_o of 1 x 10^{19} W / cm^2 and a pulse width of 45 fs. It shows that the laser pulse will ionize the first 5 states of nitrogen and the 2 states of helium much earlier in time with respect to the 6th state of nitrogen. This is due to the fact that the appearance intensity of nitrogen 6 is at least 300 times greater than the previously ionized state of either nitrogen or helium. Therefore, the laser will first push out and create an accelerating wakefield from electrons ionized from the first 5 states of nitrogen and 2 states of helium. Then it will ionize the 6th state of nitrogen which will be born into the wake.

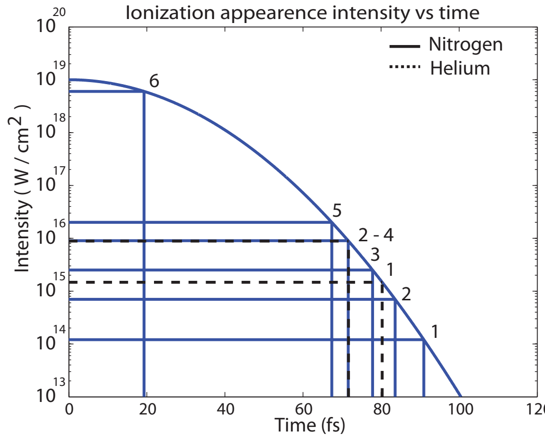

Figure 3: Ionization appearance intensity times for the first 6 states of nitrogen and 2 states of helium as ionized by a Gaussian laser pulse with a I_o of 10^{19} W / cm^2 and pulse width of 45 fs.

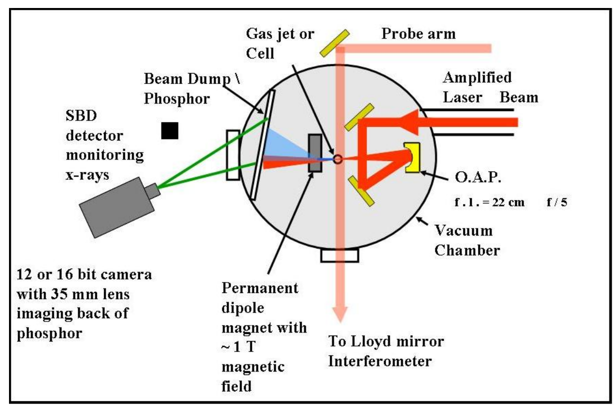

Figure 4: Experimental setup

An overview of the experimental setup is shown in figure 4. The laser pulse was focused onto the edge of a conical gas jet with a 2 mm exit diameter to create the wake. Laser light which is not coupled into driving the wake, will diffract. The diffracted light is still intense enough to ionize the lower stages of the helium and nitrogen atoms and will create a large volume of low density plasma at the end of the gas jet. Therefore, when recovering the measured plasma density profile of the experiment via Abel inversion, only the first half of the interferogram, where the plasma density is assumed to be uniform over the smaller more intense laser volume, was used. Assuming a symmetric neutral density gas profile, the plasma density profile of the first half of the interaction can be mirrored to create a full experimental density profile that the coupled laser driving the wakefield interacts with. The plasma density profile was measured on every shot, using a short $\sim$

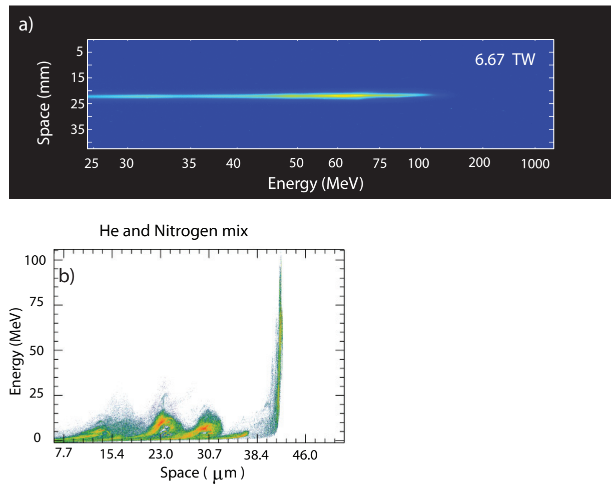

Figure 5: a) Experimentally observed dispersed electron spectrum from the HeN_2 mix. b) Electron energy vs space generated from a 2-D Osiris simulation using similar laser and plasma parameters as in the experiment.

70 fs probe beam which was sent to a Lloyd mirror interferometer. Figure 2b is a typical plasma density profile of the helium nitrogen mix and indicates a peak plasma density of $\sim$ 1.4 x 10^{19} cm^{-3}. For this density the dephasing length Ldph is $\sim$ 320 μm according to 3D nonlinear theory. The peak plasma density is nearly constant over this scale length. Electron beams that were created were dispersed by a $\sim$ 1 T permanent dipole magnet onto a phosphor screen. The phosphor screen was imaged with a 35 mm camera lens onto either a 12 or 16 bit CCD camera.

Experiments were carried out in both pure He and HeN_2 mix (90% He 10% N_2) plasmas. In general, from plasmas created from pure He gas, it was difficult to consistently generate electron beams at plasma densities below 1.5 x 10^{19} cm^{-3} . Dispersed electron spectra that were generated, appeared quasi mono-energetic having peak energies of $\sim$ 45 MeV with fluxuations in peak electron energy of $\sim$ 20-30 MeV and energy spreads of greater than 40 %. In contrast, electron spectra could be consistently generated from the HeN_2 gas mix. Figure 5a is an experimentally observed spectrum from the HeN_2 mix at a plasma density of 1.4 x 10^{19} cm^{-3} and an initial laser power of 6.67 TW. It is representative of many similar spectra obtained from the HeN_2 mix. The spectrum consists of quasi monoenergetic feature on top of a broad continuous spectrum. Similar electron spectra were created from the HeN_2 gas mix over a broad range of P / Pc from 1.5 - 3.5 which corresponds to a range of normalized vector potentials a_o of 1.75 to 2.5. It was found that the laser intensity threshold for generating an electron beam from the HeN_2 mix corresponded to the appearance intensity of N^{6+} which is 6 x 10^{18} W / cm^2. Additionally, the broad energy spectra is expected because N^{6+} electrons will be continuously ionized and injected into the wake as the laser propagates through the plasma. Electrons that are ionized and injected earlier into the wake will gain more energy than electrons injected at later times. The well defined appearance intensity threshold, as well as the broad energy spectrum are indicative of N^{6+} electrons which have been continuously injected into the wake via ionization and subsequently accelerated.

To gain further insight, a 2-D OSIRIS simulation which included the effects of ionization was preformed. The laser parameters of simulation were again closely matched to what was experimentally available using an a_o = 2.5, a laser pulse width of 40 fs (FWHM of the intensity), and a laser spot size of w_o = 6 μm. In the simulation the same mixture of helium and nitrogen gas was used as in the experiment. Additionally the plasma density profile of the simulation was chosen to approximate the experimentally measured plasma density profile. Figure 2 shows the simulated plasma density profile. The electron energy vs space, in the moving frame of the laser, at the end of the simulation is plotted for the HeN_2 in figure 5b. The simulated spectrum of the HeN_2 gas mixture, like the experimentally observed spectrum, is also a broad. Looking at where accelerated electrons are generated in the moving frame with respect to the laser it can be seen that the higher energy broad band of accelerated electrons originates in the first period of the wake. In simulations of pure He with exactly the same laser and plasma parameters, no electrons were observed to be injected into the first period of the wake. Therefore, the fact that in the simulation using the HeN_2 gas mix,that the band of accelerated electrons comes from the first period of the wake is confirmation that these electrons have been injected by the laser ionizing the 6th state of nitrogen. This result agrees with the physical picture and the experimental result reported.

CONCLUSIONS

A new method for trapping particles into a laser driven wakefield accelerator was proposed and experimentally investigated. Electrons were trapped and accelerated from a mixture of helium and nitrogen gas via laser wakefield acceleration. The qualitative properties and differences of and between electron spectra generated via ionization trapping and self-trapping were discussed. More work is necessary to better understand the physics and the limitations of injecting electrons into laser driven wakefields through ionization.A more complete analysis will be presented in another publication.

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