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# Detailed Modeling of Channel Guided Laser Wakefield Accelerators Based on Capillary Discharges

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The laser wakefield accelerator (LWFA) utilizes a high intensity ($10^{18}$ W/cm$^2$) short pulse (50 fs) laser to drive a large amplitude plasma wave suitable for accelerating electrons [1]. The accelerating gradient produced by a LWFA can be on the order of 100 GeV/m. Because of the high laser intensity required, the laser spot size is often only tens of microns, and the acceleration length is limited to a few millimeters by diffraction. To overcome this limitation, a plasma channel can be used to guide the laser pulse over much longer distances [2]. A capillary discharge is a relatively simple device that can be used to create a plasma channel. It typically consists of a 500 $\mu$m diameter hole bored through the central axis of a polypropylene cylinder. Electrodes are placed on either end and a high voltage discharge creates a plasma via ablation of the capillary walls. Generally, the discharge is triggered by the creation of a seed plasma by means of a second, higher voltage discharge, or more recently, by laser ablation of the capillary walls [3]. As the main discharge progresses, the on-axis electron temperature rises. This causes the on-axis conductivity to rise which results in further heating driven by the discharge current. This leads to an on axis density depression due to the fact that the pressure in the capillary is nearly constant (the acoustic time is fast compared to the discharge time). This density depression is suitable for guiding of high intensity laser pulses [4].

Because of the fact that the accelerating fields coexist with large discharge currents, it is of interest to examine the associated magnetic fields and study their effects on electrons injected into the capillary. Estimates of the magnetic fields inside and outside a capillary discharge were discussed in Ref. [5]. The peak field is about 1 kG for typical discharge parameters. If the discharge current and injection velocity are anti-parallel, the field acts like a focusing lens for the injected particles. As discussed in Ref. [5], the effects are not expected to be detrimental to acceleration. The simulations presented below include the effects of the discharge magnetic field.

The polypropylene walls of the capillary have the chemical formula $CH_2$, so that the plasma consists of carbon ions, hydrogen ions, and electrons. The typical electron temperature is 3-4 eV, so that the hydrogen atoms are expected to be 100% ionized, and the carbon atoms are expected to be doubly ionized on average. For typical LWFA parameters, the laser photoionizes two more electrons to produce quadrupally ionized carbon. The photoionization process can affect the laser propagation and wakefield excitation.

Injecting electrons into a LWFA is difficult because of the fact that the injected bunches have to be timed to the laser pulse within tens of femtoseconds in order to be optimally accelerated. The properties of tunnel ionized plasmas are the basis for an optical injection scheme known as Laser Ionization and Ponderomotive Acceleration [6]. In this scheme, a multi-terawatt laser pulse is focused onto the edge of a nitrogen gas jet. Electrons are released from the innermost shells of the nitrogen atom only when the field is extremely high, and therefore they receive a very large ponderomotive impulse and are ejected from the laser focus with high energy. Furthermore, there is a relation between the angle of ejection and the energy of the particle that can be exploited to select a monochromatic group of particles for injection. Figure 1 shows the results of 3D particle-in-cell (PIC) simulations of the LIPA injector. The simulation was carried out using turboWAVE [7] operating in fully explicit mode and running on 512 processors. In the simulation, a 2 TW, 50 fs laser pulse was focused onto the edge of a nitrogen gas jet with an atomic density of $10^{17}$ $cm^{-3}$. Panel (a) shows that the largest number of electrons are ejected at an angle of about 30 degrees with respect to the laser axis. Panel (b) shows that at this angle, the average electron energy is about 1.5 MeV. Panel (c) gives the energy spread as around 10%, and panel (d) gives the pulse length as around 10 fs. Such an electron bunch is ideally suited for injection into a LWFA.

The setup used to inject the LIPA electrons into a multi-stage LWFA is shown in Fig. 2. A 10 TW, 50 fs laser pulse is split into two parts: a 2 TW injection beam and an 8 TW acceleration beam. The injection beam is focused tightly onto a nitrogen gas jet to produce 1.5 MeV electrons. The capillary is oriented to capture these electrons. The acceleration beam is focused more gradually into the capillary. The capillary consists of three segments of varying density. The segmented capillary is used to obtain energies beyond the dephasing limit [8]. The output from the LIPA simulation was used as an input into a 2D simulation of the acceleration section (i.e., the capillary). The simulation included magnetic fields due to the discharge as well as photoionization of carbon ions. The effects of the magnetic field were not significant. The main effect of ionization was to raise the density in the capillary by 50%. The increase in density was uniform throughout most of the laser pulse (because the ionization rate is a nonlinear function of intensity), so that a simple rescaling of the initial density is all that is required to preserve the guiding properties of the channel. The laser evolution was also slightly affected by photoionization in that a blue shift occurred at the head of the pulse. This did not significantly affect acceleration, and was far less disruptive than the distortions that occurred due to pump depletion. The final result is shown in Fig. 3, which shows the spectra of the accelerated electrons at the end of each stage of the segmented capillary. After the first stage, the energy is about 310 MeV and the energy spread is 5%. As the acceleration continues, a tradeoff is made between beam energy and beam quality. At the end of the third stage, the energy is 790 MeV, but the energy spread increases to 9%.

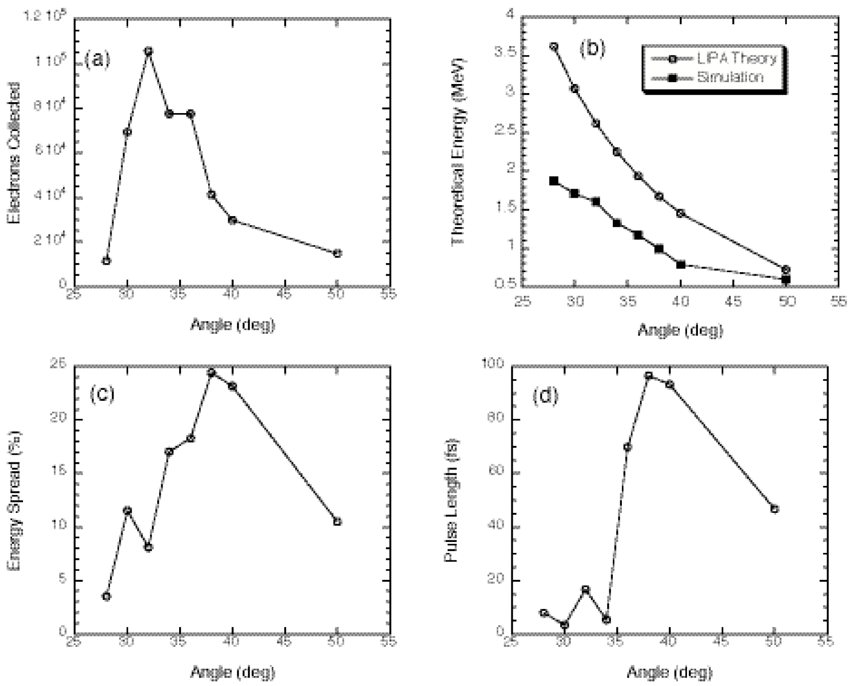


*Fig. 1 Characteristics of LIPA electrons collected by 60-μm aperture*

In conclusion, a capillary discharge is a simple device which can be used to extend the length of a LWFA by guiding the laser pulse in a plasma channel. The magnetic fields generated by the discharge do not appear to preclude external injection of electrons. The photoionization of carbon ions is significant, but due to its threshold behavior it can be compensated for by reducing the initial electron density in the capillary. A segmented capillary can be used to increase the final energy of the accelerator. A 10 TW, 50 fs laser pulse can be used to generate, inject, and accelerate electrons to 800 MeV with an energy spread of less than 10%.

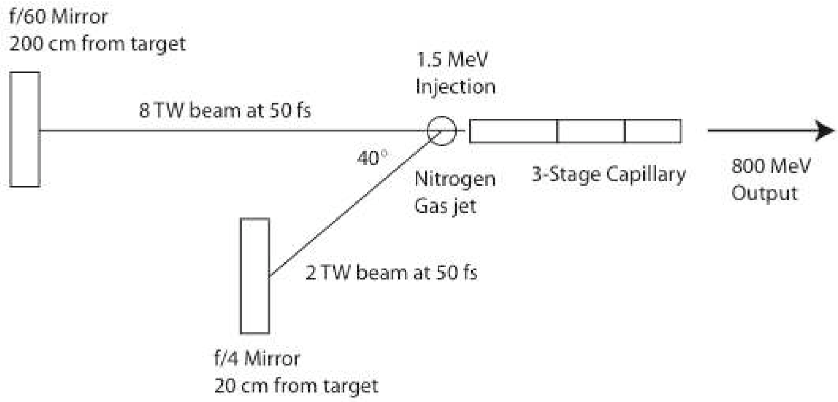


*Fig. 2 Setup for LIPA Injection*

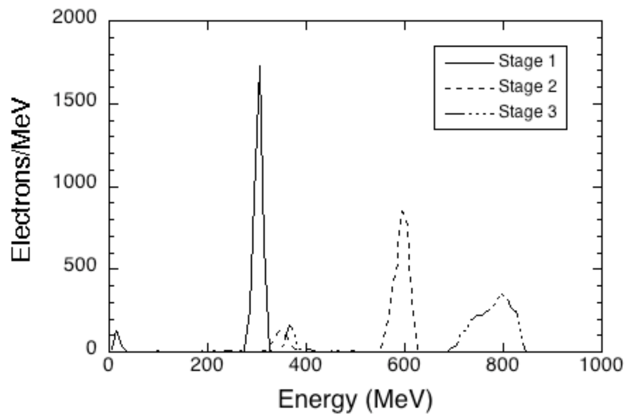


*Fig. 3 Spectra of the accelerated particles after one stage (solid line), two stages (dotted line), and three stages (solid-dotted line)*

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