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Plasma channels produced by a laser-triggered high-voltage discharge

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A plasma waveguide scheme for high-intensity laser guiding with densities and lengths suitable for laser-plasma particle accelerators is presented. This scheme uses a laser-triggered high-voltage discharge, presents negligible jitter, allows full access to the plasma, and can be scaled to large distances. Experimental results showing the feasibility of this scheme are presented.

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High-intensity ($I > 10^{17}$ W cm^{-2}) laser guiding over lengths greater than a centimeter is one of the key issues for future laser-plasma accelerators [1–4] and other applications, such as x-ray lasers [5,6], harmonic generators [7], or advanced laser schemes [8]. In the plasma accelerator concept, an intense, ultrashort laser pulse interacts with a plasma of adequate electron density to produce high amplitude (hundreds of GV/m) plasma waves moving in the laser propagation direction at a velocity close to the speed of light c. Since the strongest waves are generated at the focal spot of the laser pulses, the length of a plasma accelerator is approximately equal to the Rayleigh length of the focusing optical system, typically between 0.5 and 2 mm. This leads to energy gains of up to hundreds of MeV, which have been measured in recent experiments [9,10]. The energy gains can be greatly enhanced by extending the interaction length (i.e., the length where the laser beam remains focused) beyond the Rayleigh length by using a guiding scheme.

In this case the maximum energy of the accelerated electrons is determined by the detuning length [4] between the accelerated electrons and the accelerating structure (plasma waves). For the parameters of current experiments the detuning length is in the centimeter range and the use of a guiding technique could increase the energy gain above 1 GeV.

Several schemes have been proposed and tested to achieve extended guiding, including propagation in capillary tubes [11–13], laser pulse self-focusing [14–17], and several types of preformed plasma waveguides [18–25]. The guiding schemes based in the preformation of a fully ionized plasma waveguide seem to be the best candidates for guiding laser pulses in electron accelerators. Preformed plasma waveguides have been achieved by ionizing and heating a linear region of gas, either by using high-voltage discharges inside capillaries [22–25] or by using lasers with linear focusing optics such as axicons and cylindrical lenses or mirrors [18–21]. These methods have been able to create guiding channels in the centimeter range and a few millimeters long respectively, and open the path to laser-plasma GeV electron accelerators, with current laser technology.

In this Rapid Communication, we describe a method for producing plasma channels with the capability of guiding high intensity laser pulses, which addresses the key issues of laser-plasma accelerators. In our configuration, a primary laser pulse is used to trigger a fast high-voltage discharge between two electrodes, consisting of two stamped cones with apertures in their apexes, aligned facing each other at the chosen guiding distance, in a gas background. The triggering laser pulse propagates in the direction of the discharge and is focused through the cathode aperture. This laser pulse should be intense enough to completely ionize the gas near the cathode and initiate the discharge. To obtain a faster evolution of the plasma line into a guiding structure (with an electron density local minimum on axis) and ensure the full ionization of this plasma, the electric field applied between the electrodes should be high enough to allow the acceleration of the electrons, between collisions, to energies above the ionization potentials of the gas; otherwise, the multielectron ionization process can be longer or incomplete. This condition can be relaxed in the case of laser triggering with high intensity laser pulses due to the instantaneous creation of a fully ionized plasma longer than the mean free path of the electrons in the discharge. As in other channeling schemes, hydrogen or helium are the best gases to be used as they easily reach full ionization. The strong electric field between the two apexes ensures the straightness of the initial plasma line. After the fast plasma production stage, a high-voltage capacitor bank is discharged through the thin plasma line, which heats and evolves into a waveguide. The desired waveguide characteristics are obtained by controlling the gas pressure, and the parameters of the discharge circuit. This method presents virtually no jitter, since it can be triggered by a laser pulse with the same origin as the propagating pulse, and has a number of additional attractive features: high reproducibility, high device lifetime, optical access to the entire plasma in the transverse direction, and low cost since it does not require special optics or energetic laser beams to ionize and heat the whole plasma. The energy of the laser used in our scheme is not required to grow with increasing channel length.

The implementation of this method was performed with the setup presented in Fig. 1. Figure 1(a) shows the electrical setup. The two electrodes, cathode (CA) and anode (AN) are made of 0.5-mm-thick copper foil with stamped 90^o cones

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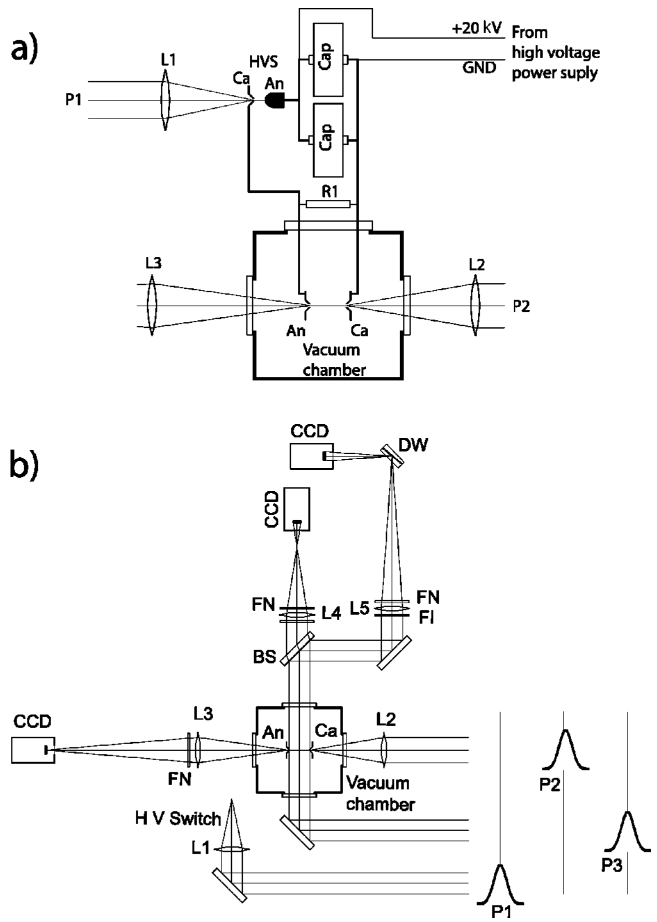

FIG. 1. Experimental setup: (a) electrical setup, (b) optical setup.

with 0.15-mm-diameter holes in their apexes. They are aligned in a small vacuum chamber and connected to a capacitor bank, made of up to six low inductance ceramic 1.7 nF capacitors, through a laser triggered spark gap high voltage switch (HVS). In these experiments the capacitor bank was charged to 20 kV. A 2-MΩ resistor R1 ensures the proper operation of the HVS.

In this experiment we have used the L^2I laser, a Terawatt-level system based on the chirped-pulse amplification concept [26]. A Ti:sapphire oscillator (Coherent Mira 900F, pumped by a 10 W Verdi) produces 100 fs pulses at a peak wavelength of 1053 nm, with a bandwidth of up to 18 nm. The grating stretcher used in these experiments had a limited spectral window that narrowed the output bandwidth down to 4 nm, with a corresponding stretched pulse width of 600 ps. The pulses are subsequently chopped at a 10 Hz rate and amplified in a Nd:YAG pumped, Ti:sapphire regenerative amplifier, where energies above 2 mJ are typically obtained. A double set of Pockels cells between crossed polarizers placed at the output of this amplification stage allows a pulse contrast of $>10^6$, which is enough to prevent spurious triggering sequences for this experimental configuration. The pulse train is sent to a double-pass, 16-mm Nd:phosphate amplifier, where its energy is amplified up to 800 mJ, at a maximum rate of one shot per minute. Finally, a pair of large aperture diffraction gratings compresses the amplified pulses to 700 fs, with an efficiency that allows 1 TW laser pulses to reach the target.

The optical setup is presented in Fig. 1(b). The compressed main beam was divided into beams P1, P2, and P3 with 33%, 44%, and 7% of the main beam energy respectively. Beam P1 is sent directly to trigger the HVS, where it is focused on the cathode aperture with an $f/5.6$ lens. Beam P2 passes through a fixed delay line and hits the discharge cathode inside the vacuum chamber 20 ns after the HVS triggering. This beam is focused with an f/7 lens on the center of the cathode aperture. It enters the vacuum chamber through a 10-mm-thick, antireflection coated glass window. The delay between beams P2 and P3 can be varied between -3.9 and 73 ns adjusting the delay line of beam P3, which is used for plasma diagnostics. After passing transverse to and collimated through the plasma, it is split into two beams: one is used to obtain shadowgraphic images of the plasma, the other to obtain an interferogram of the same region, by passing it through a shearing interferometer DW made of two uncoated glass wedges. Lenses L4 and L5, are used to image the plasma plane into two charge coupled device (CCD) cameras. Adequate neutral density filters FN are used to reduce the intensity of the light reaching the CCD cameras, and a 10-nm-bandwidth interference filter centered at 1053 nm is used on the interferometry diagnostic to increase the interferogram contrast. The phase shifts of the interferograms were calculated automatically by means of a fast Fourier transform method [27]. The plasma electron density was then obtained by Abel inversion of the phase shifts assuming cylindrical symmetry. A current probe, consisting of a copper coil placed near the cable conducting the main discharge current, was used to follow qualitatively the discharge current. A signal proportional to the variation of the current in time was observed with an oscilloscope, triggered by means of a fast photodiode, monitoring a pulse leak from a mirror. With this information, it was possible to measure the two relevant time intervals before and after the beginning of the discharge current, respectively: τ_1 is the time elapsed since the discharge is triggered by beam 2, and τ_2 is the delay before the probe pulse propagates through the plasma.

After a pumping down to 5×10^{-2} mbar, the vacuum chamber was filled with He at a pressure between 100 and 500 mbar. The gap distance (distance between the anode and cathode apexes) was varied between 5 and 25 mm. For gap distances in the centimeter range, He pressures between 100 mbar and 500 mbar and a potential of 20 kV, the mean energy of the electrons is less than 15 eV, clearly below the first (24.6 eV) and second (54.4 eV) ionization potentials of He.

The fact that the same initial laser pulse is used to trigger both the discharge and the HVS makes this experiment very sensitive to laser prepulses, since even a small one ($<10^6$) was enough to start a slow discharge. Another important parameter to obtain straight plasma lines is the ratio E/P, where E is the electric field and P is the pressure. This ratio is inversely proportional to the amount of random transverse motion of the starting ionizing electrons, and therefore also to the plasma line diameter and uniformity. With this setup we have obtained straight, uniform, and reproducible thin plasma lines for laser pulse contrasts higher than 10^6, He

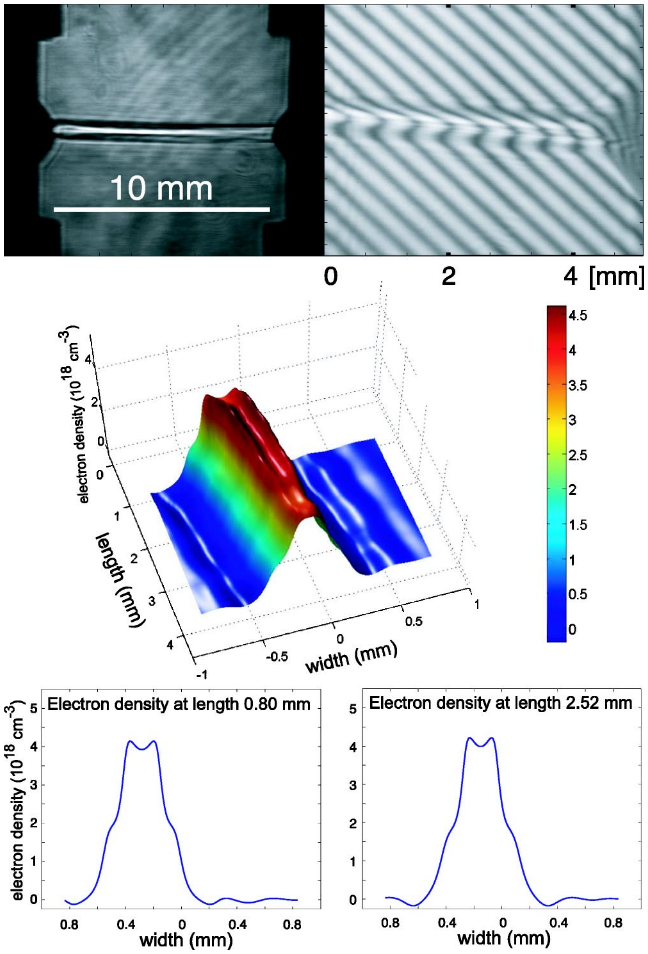

FIG. 2. (Color online) Experimental characterization of a plasma channel and density retrieval. Top, shadowgram (left) and shearing interferogram (right); middle, retrieved electron density; bottom, lineouts at $x=0.80$ mm (left) and $x=2.58$ mm (right). In this shot the gap was 10 mm and the He neutral density was 7.4×10^{18} cm^{-3}. The time delays were $\tau_1=-37.5$ ns and $\tau_2=73.2$ ns.

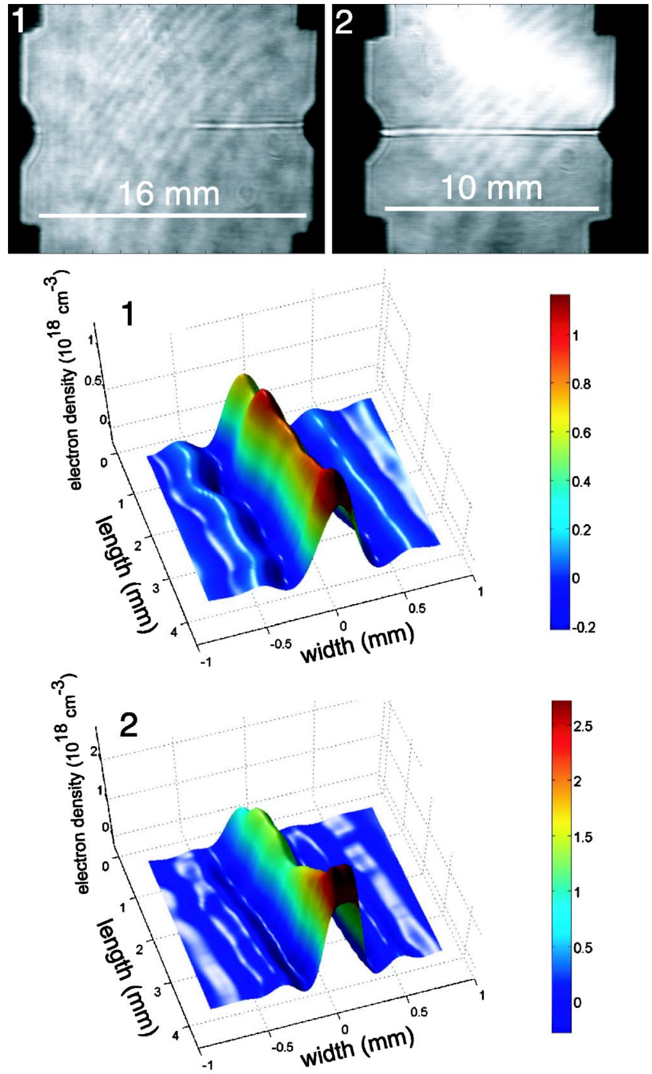

FIG. 3. (Color online) Shadowgraphy and retrieved electron density for (1) gap 16 mm, neutral He density 3.7×10^{18} cm^{-3}; (2) gap 10 mm, neutral He density 1.0×10^{19} cm^{-3}.

pressures between 100 and 200 mbar, and gaps from 8 to 16 mm. Plasma lines with a guiding structure, i.e., with an on-axis local minimum of density, only appeared for pressures above 200 mbar. This is due to the limited length of the delay lines and to the more effectiveness of the plasma heating for higher density plasmas. A typical example of such a plasma is presented in Fig. 2. This plasma was obtained for a 10-mm gap and a He pressure of 294 mbar, corresponding to a neutral density of 7.4×10^{18} cm^{-3}. For this particular shot we had $\tau_1=-37.5$ ns and $\tau_2=73.2$ ns, the negative value of τ_1 indicating that the discharge was triggered by a prepulse. The earlier initiation of the current results in a longer τ_2, that is, we can measure the plasma density at times later than those imposed by our delay lines. In this shot, the combined effect of a long τ_2 and a denser plasma, where a more effective heating makes the plasma expand faster and evolve towards a guiding structure, allowed us to observe a plasma channel. The interior of the plasma channel fits well a parabolic profile compatible with matched guiding of a laser beam focused to a 35-μm-diameter spot size. Another interesting feature of the plasma profile is the appearance of a step at half the maximum electron density, clearly seen in the density lineouts, which is a strong evidence of He full double ionization. One may also observe that the plasma density is smaller than twice the initial He neutral density; this is expected since the channel formation requires an expansion of the hot core of the plasma line.

Figure 3 shows two shots where the plasma is seen in the earlier stages of development with only partial ionization. These were obtained with the following parameters: (1) 16 mm gap, pressure of 254 mbar corresponding to a neutral density of 3.7×10^{18} cm^{-3}, $\tau_1=36.1$ ns and $\tau_2=0.4$ ns; (2) 10 mm gap, pressure of 408 mbar corresponding to a neutral density of 1.0×10^{19} cm^{-3}, $\tau_1=14.5$ ns and $\tau_2=21.2$ ns. In these two shots the plasma line is straighter and more uniform than that of Fig. 2. We have verified that a degradation of these features is typical of those plasmas triggered by prepulses. With the profiles obtained for these channels, we have performed one-to-one full scale modeling particle-incell simulations of the matched propagation of intense laser pulses. Our simulations in this channel show laser guiding over the full channel length, and electron acceleration up to 1.1 GeV and 300 MeV for laser pulses with durations of 150 fs and energies of 5.6 J and 1.0 J, respectively [28].

In conclusion, we have proposed a simple and low cost plasma channel creation scheme that can be advantageously applied in laser-plasma particle accelerators or other applications requiring high intensity laser guiding in a H or He plasma. This method has no inherent jitter, allows full access to the plasma and is scalable to, at least, 5 cm. Our results show the formation of straight and uniform plasma lines and confirm the creation of guiding structures with an approximate parabolic density profile with a local minimum density on axis. These channels are suitable for guiding intense, short laser pulses and sustaining wakefield accelerating gradients capable of achieving GeV energy gains in 1 cm.

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