Laser-driven plasma waves in capillary tubes

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The excitation of plasma waves over a length of up to 8 cm is demonstrated using laser guiding of intense laser pulses through hydrogen-filled glass capillary tubes. The plasma waves are diagnosed by spectral analysis of the transmitted laser radiation. The dependence of the spectral redshift—measured as a function of filling pressure, capillary tube length, and incident laser energy—is in excellent agreement with simulation results. The longitudinal accelerating field inferred from the simulations is in the range of 1–10 GV/m.

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Electrons accelerated in laser wakefield accelerators (LWFAs) [1–3] acquire momentum from the electrostatic fields of a plasma density wave or wake, excited by an intense laser pulse passing through plasma. As they can achieve ultrarelativistic energies over very short distances, they have attracted great interest as novel routes to a new generation of ultracompact accelerators, which could be relevant to a wide range of applications, including high-energy physics and compact free-electron lasers. At high laser intensities large amplitude plasma waves with longitudinal electric fields, up to hundreds of GV/m, are excited, which are several orders of magnitude higher than those possible in conventional accelerators. When electrons are injected into the accelerating regions of such plasma waves, either from an external source [4] or by self-trapping of plasma electrons by nonlinear effects, they have been observed to reach energies up to hundreds of MeV over acceleration distances of only a few mm [5–8]. However, even with fields as high as 100 GV/m, the acceleration distance must be extended to tens of cm in order to reach electron energies of, say, tens of GeV. This is a range not yet realized experimentally.

There are two main requirements that must be fulfilled before a viable multi-GeV LWFA can be realized. First, the intense laser pulse driving the plasma wave must be guided over the full length of the accelerator. Second, the dephasing length, which is the distance over which the accelerating electrons outrun the accelerating region of the plasma wave, must be at least as long as the accelerating medium. To date, most experiments have been performed with a few mm long gas jets, where self-guiding due to relativistic self-focusing provides a simple guiding solution. However, the threshold power for self-focusing is, for a given laser wavelength, inversely proportional to the plasma density, thus requiring a minimum density for a given laser. As an example, for a laser with 10 TW peak power and 800 nm wavelength, this density is $n_e \approx 3 \times 10^{18}$ cm^{-3}. An alternative approach is to guide the laser in a preformed plasma channel produced by an electric discharge in a gas-filled capillary tube. In this way guiding up to several centimeter long plasma waveguide has been demonstrated [9]. However, this approach is limited to plasma densities in excess of $n_e \sim 10^{18}$ cm^{-3}. Long dephasing lengths require very low plasma densities [3], which is clearly in conflict with the density requirements for relativistic self-guiding and guiding by discharge-formed plasma channels.

A method of guiding the intense laser pulse over long distance, while allowing very low plasma density, is thus required. This can be realized using capillary tubes as waveguides [10] where guiding is achieved by reflection from the walls. Laser guiding through gas-filled capillary tubes allows for a smooth transverse profile in monomode propagation [11] and a minimum attenuation of the laser pulse through refraction losses. As a first step in developing the waveguide as a medium for a wakefield accelerator, we have characterized the properties of the plasma wave in the moderately nonlinear regime over several centimeters. Working in the linear or moderately nonlinear regime allows control of the amplitude of the plasma waves while providing a focal spot of sufficient dimensions to effectively create quasi-one-dimensional longitudinal oscillations as shown by theoretical studies [12,13]. This regime enables a controlled and reproducible injection of an external electron bunch into the accelerating field, which provides a means of attaining high stability and reproducibility for future staging of several LWFA stages.

In this paper, we report on an observation of plasma waves excited by a guided high-intensity laser pulse inside hydrogen-filled capillary tubes with lengths up to 8 cm. The plasma wave excitation is diagnosed using a method based on spectral modifications of the laser pulse, due to local spatiotemporal variations of the density of the plasma [14].

An experiment was performed using the high-intensity Ti:sapphire laser system at the Lund Laser Centre which delivers up to 40 TW onto the target, with a full width at half maximum (FWHM) pulse duration down to $\tau_L = 35$ fs. The setup is shown schematically in Fig. 1. The 30-mm-diameter beam was focused with an $f = 1.5$ m spherical mirror at the entrance of a capillary tube. A deformable mirror was placed after the compressor (not shown) to correct the main aberrations of the phase front in the focal plane.

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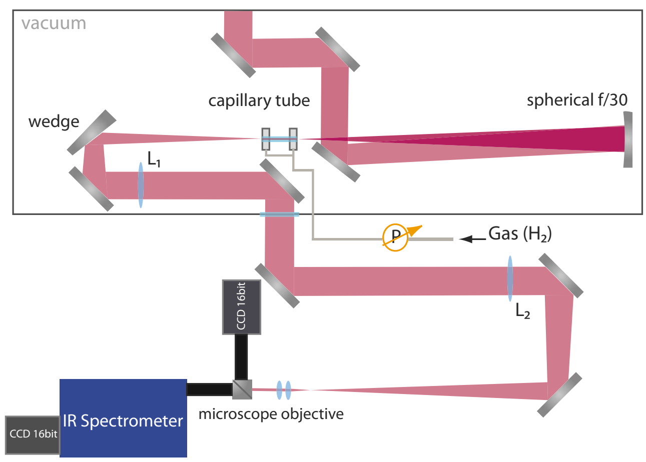

FIG. 1. (Color online) Schematic view of the experiment setup. Elements within the gray line box are under vacuum.

The laser beam transmitted through the capillary tube was attenuated by reflecting it on an optically flat glass wedge and then collimated by an achromatic $f_1=1$ m lens (L_1), which could be translated in vacuum along the beam axis to collect light either from the focal plane (i.e., with the capillary tube removed) or from the exit plane of the tube. The beam was then focused by a $f_2=1$ m achromatic lens (L_2) and magnified $10\times$ by a microscope objective. The beam was split in two parts. Focal spot or capillary tube output images were recorded by a 16-bit charge-coupled device (CCD). The transmitted part was sent to a visible to near-infrared imaging spectrometer equipped with a 16-bit CCD camera. The spectral resolution was 0.1 nm.

Glass capillary tubes with inner radius $r_c=50$ μm and length varying between 1.2 and 8.1 cm were used. Hydrogen gas flowed into the tubes through two thin ($\sim$100 μm) slits located between 2.5 and 5 mm from each end of the tube. The filling pressure was varied between 0 and 70 mbar. Each capillary tube could be used for at least 100 laser shots, when the laser beam remained well centered at the capillary entrance. Pointing variations due to thermal drifts and mechanical vibrations were therefore minimized or compensated for. Laser guiding at input intensities up to 10^{18} W/cm^2 was achieved with more than 90% energy transmission in evacuated or hydrogen-filled gas tubes up to 8 cm long.

For the data presented here, in order to investigate the moderately nonlinear regime, the input intensity was kept lower than 3×10^{17} W/cm^2. The laser pulse duration was $\tau_L=45\pm5$ fs and the associated bandwidth was approximately 25 nm (FWHM); each pulse had a small negative linear chirp (-550 fs^2), i.e., short wavelengths preceded longer wavelengths, and the center wavelength was 786 nm. The energy distribution in the focal plane exhibited an Airy-like pattern with a radius at first minimum of $r_0=40\pm5$ μm.

Spectra of the laser light transmitted through gas-filled capillary tubes exhibit blue and red broadening. In the range of parameters relevant to this experiment, spectral modifications of the wake-driving laser pulse—after propagating in the plasma over a large distance—are mainly related to changes in the index of refraction of the plasma during the creation of the plasma wave. The front of the laser pulse creates an increase in electron density, leading to a blueshift at the front of the pulse, while the rear of the pulse creates a decrease in electron density with larger amplitude, and thus a redshift of the spectrum. This effect has been proposed [14] to determine the amplitude of the electron plasma density perturbation in the linear or moderately nonlinear regime.

An averaged wavelength shift $\Delta\lambda(l)$ is calculated from the experimentally measured spectra $S(\lambda,l)$ at the exit of a capillary of length l and is defined as

$$\Delta\lambda(l)=\frac{\int_0^\infty \lambda S(\lambda,l)d\lambda}{\int_0^\infty S(\lambda,l)d\lambda}-\lambda_L, \tag{1}$$

where $\lambda_L=[\int_0^\infty S(\lambda,l=0)d\lambda]^{-1}\int_0^\infty \lambda S(\lambda,l=0)\simeq 2\pi c/\omega_L$ is the center wavelength of the incident laser pulse in vacuum and ω_L is the laser frequency. For an underdense plasma and laser intensity well above the ionization threshold, when the blueshift due to gas ionization inside the interaction volume V can be neglected and the wavelength shift given by Eq. (1) remains small compared to λ_L, this shift is directly related to the energy of the plasma wave electric field E_p excited in the plasma [14],

$$\frac{\Delta\lambda(l)}{\lambda_L}\simeq\frac{1}{16\pi\mathcal{E}_{out}}\int_V E_p^2 dV, \tag{2}$$

where $\mathcal{E}_{out}$ is the total energy of the transmitted pulse. For monomode propagation of a laser pulse with Gaussian time envelope, generating a wakefield in the weakly nonlinear regime, the wavelength shift can be expressed analytically. For small energy losses, it is proportional to the peak laser intensity on the capillary axis and to the length of the capillary and exhibits a resonantlike dependence on gas pressure described by the function $D(\Omega)$ as

$$\Delta\lambda(l)\simeq\left[0.178+1.378\frac{c^2}{(\omega_p r_c)^2}\right]\left(\frac{\omega_p}{\omega_L}\right)^3 a_L^2 D(\Omega)l, \tag{3}$$

where $a_L=eE_L/m_e\omega_L c$ is the normalized amplitude of laser electric field E_L, $D(\Omega)=\Omega\exp(-\Omega^2/4)$ with $\Omega=\omega_p\tau_L/\sqrt{2\ln 2}$, and $\omega_p=\sqrt{n_e e^2/\epsilon_0 m_e}$ is the electron plasma frequency.

The value of the wavelength shift $\Delta\lambda$ obtained from measured spectra is plotted as a series of black squares in Fig. 2 for a tube of length 7.1 cm as a function of filling pressure. Nonlinear laser pulse propagation in the gas-filled capillary tube including optical field ionization of gas, wakefield generation, and the self-consistent laser pulse spectrum modification was simulated numerically using the code described in [12]. The parameters used at the capillary entrance are $\tau_L=51$ fs, with a negative chirp, and an incident laser energy $\mathcal{E}_L=0.12$ J, with a radial profile corresponding to the one measured in the focal plane in vacuum, averaged over the angle. Simulation results are plotted as a red triangle curve in Fig. 2. For comparison, the analytical behavior given by Eq. (3) is plotted as a blue dashed curve, for the same $(\tau_L,\mathcal{E}_L)$. The simulated wavelength shifts fit closely the experimen-

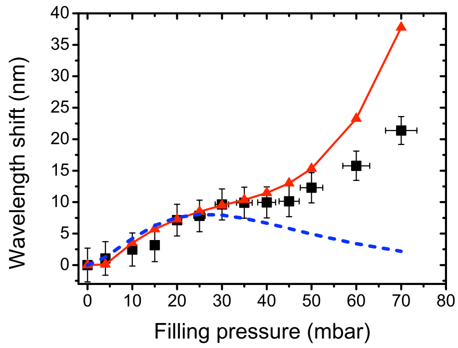

FIG. 2. (Color online) Wavelength shift as a function of hydrogen H_2 filling pressure at the exit of a 7.1-cm-long capillary tube obtained from experimental data (black squares); simulation results (red triangle curve) with $(\tau_L, \mathcal{E}_L)=(51\ \text{fs}, 0.12\ \text{J})$ and a negative chirp; analytical result from Eq. (3) for the same parameters (dashed blue line).

tally measured ones up to a filling pressure of 50 mbar. Analytical curve and measured and modeled wavelength shifts have the same behavior up to the linear resonant pressure of 25 mbar ($n_e \simeq 1.2\times 10^{18}\ \text{cm}^{-3}$). For pressures higher than 25 mbar, the experimental data and simulation exhibit a larger redshift than the analytical prediction. The analysis of the pulse evolution in the simulation shows that a steepening of the laser pulse front edge, due to propagation in the ionizing gas [15], occurs followed in time by pulse self-modulation [12]. A steepened pulse front is more efficient than a Gaussian time envelope to generate the wakefield at pressures larger than the resonant one. The values of the wavelength shift in the simulation are larger than the measured ones for pressures above 50 mbar. This behavior is related to the assumption of cylindrical symmetry used in the simulation, which leads to more pronounced nonlinear effects including laser pulse shortening [12,16].

Figure 3 shows examples of the spectra of the laser pulse measured (black lines) in the focal plane in vacuum [Fig. 3(a)] and at the output of the 7.1 cm capillary tube and the corresponding simulated spectra (dashed red lines) for filling pressures of 30 mbar [Fig. 3(b)] and 40 mbar [Fig. 3(c)]; two different shots are shown for each pressure.

All spectra are normalized to their maximum amplitude and integrated over the radial coordinate. The spectral modifications in the experiment and the simulations are in excellent agreement over a large range of amplitude. This agreement on the detailed structure of the spectra confirms the one, shown in Fig. 2, achieved on the wavelength shift, which is an integrated and averaged quantity.

The wavelength shift measured at the output of the capillary tubes as a function of the tube length is plotted in Fig. 4 for different filling pressures as well as the corresponding simulated results. A linear behavior of the wavelength shift as a function of length is observed at 20 mbar. The fit of experimental data by simulation results demonstrates that the plasma wave is excited over a length as long as 8 cm. As the pressure is increased, the nonlinear laser pulse evolution is amplified with the propagation length leading to a larger plasma wave amplitude.

The wavelength shift as a function of input laser energy is

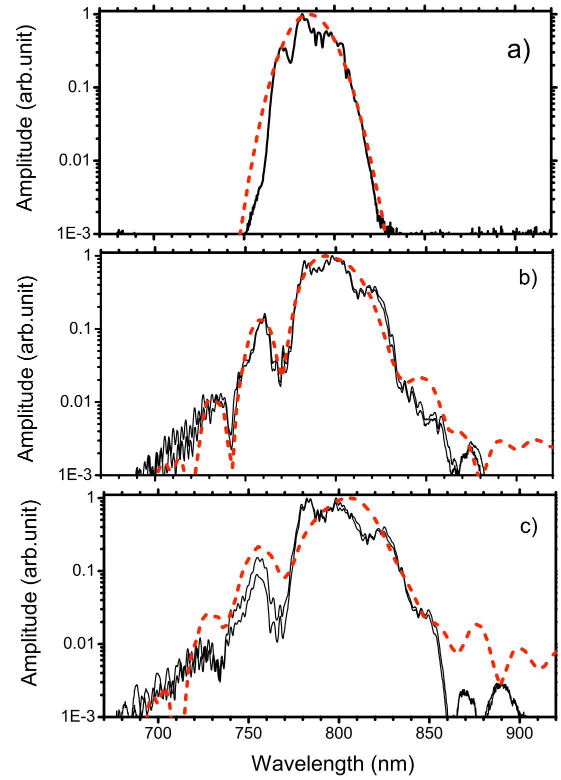

FIG. 3. (Color online) Spectra measured (black lines) (a) in the focal plane in vacuum and at the output of the 7.1 cm capillary tube for filling pressures of (b) 30 and (c) 40 mbar; two shots are shown for each pressure; corresponding simulated spectra (red dashed line).

shown in Fig. 5 at the exit of a 7.1-cm-long capillary tube for a filling pressure of 40 mbar, obtained from experimental data, simulation results, and analytical prediction. For $\mathcal{E}_L > 0.1$ J, the growth of the wavelength shift is faster than the linear one predicted analytically and the experimental and numerical results are in excellent agreement. For lower energy ($\simeq 0.05$ J), gas ionization occurs closer to the maximum of the pulse and, combined with radial structure, leads to a more pronounced steepening of the front edge of the pulse and increased wakefield amplitude and wavelength

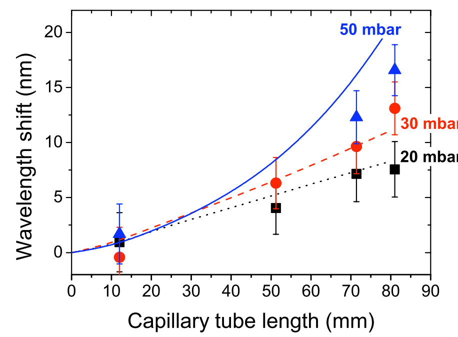

FIG. 4. (Color online) Wavelength shift measured at the output of the capillary tubes as a function of the tube length for filling pressures of 20 mbar (black square), 30 mbar (red dots), and 50 mbar (blue triangles) and the corresponding simulated shifts (dotted, dashed, and solid lines).

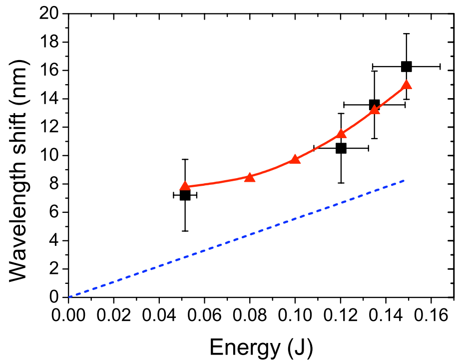

FIG. 5. (Color online) Wavelength shift as a function of input energy, at the exit of a 7.1-cm-long capillary tube for a filling pressure of 40 mbar obtained from experimental data (black squares), simulation results (red triangle curve), and analytical prediction (blue dashed curve).

shift compared to the analytical prediction [Eq. (3)].

In conclusion, we have generated and characterized a laser-driven plasma wave in the moderately nonlinear regime over a distance as long as 8 cm inside dielectric capillary tubes. An excellent agreement is found between the measured wavelength shift and the results from simulations as concerns pressure, length, and energy dependences. In the linear and weakly nonlinear regimes, this diagnostic provides a robust and reproducible measurement of the plasma wave amplitude over a long distance. The value of the longitudinal accelerating field in the plasma obtained from the simulation is in the range of 1–10 GV/m. The average product of gradient and length achieved in this experiment is on the order of 0.4 GV at a pressure of 50 mbar; it could be increased to several GV by extending the length and diameter of the capillary tube with higher laser energy.

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