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Influence of laser pulse duration on relativistic channels

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A high-power (10 TW) laser is employed to generate relativistic channels in an underdense plasma. The lengths of the channels are measured by imaging the Thomson-scattered light, and the gas densities are determined through the forward Raman scattered light. The laser-pulse parameters are varied and their impact on the channel formation is studied. It is found that increasing the laser pulse duration in many cases produces longer channels, even as this implies reducing the laser peak power. A theoretical discussion is presented, proposing an explanation of the experimental results. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1449890]

I. INTRODUCTION

The propagation of short, ultra-high intensity laser pulses in plasmas has in recent years become a subject of great interest and activity. One reason is the possibility to form relativistically self-guided channels in which the high-intensity laser pulses can propagate over several Rayleigh ranges.[1] This opens new doors for a wide range of applications requiring very high laser intensity over extended lengths, e.g., in connection to various x-ray laser schemes and laser-driven particle acceleration.[2–4] Another reason for a strong increase in activity in this field is the recent very fast development in high-power laser technology. Compact laser systems with peak power in the terawatt range, based on the chirped-pulse amplification (CPA) technique and with titanium-doped sapphire (Ti:s) as an amplifying medium, are becoming widespread. The rapid increase in peak power and compactness of these systems has, to a large extent, been achieved by a shortening of the pulse duration. Tabletop multi-terawatt laser systems with a pulse duration of only a few tens of femtoseconds are now available.[5,6] However, not all high-power phenomena can benefit from an increase in peak power if the pulse duration becomes too short. Here we report results of systematic experimental studies on how the laser pulse duration influences the formation of relativistic channels. In particular, the length of the channels is investigated under different conditions.

The interaction between a gas with low atomic number and a short, high-intensity laser pulse can be described briefly as follows. The leading edge of the pulse ionizes the gas and creates a plasma with which the main part of the pulse interacts. The plasma frequency is given by $\omega_p = \sqrt{e^2 n_e / \gamma m_e \epsilon_0}$, where e, m_e and n_e are the electron charge, mass and density, respectively. The relativistic factor of the electron motion, γ, is associated with the electron quiver motion transverse to the laser propagation, and is consequently a function of the laser intensity. In terms of light propagation, the laser pulse senses an index of refraction, $n = \sqrt{1-\omega_p^2/\omega_0^2}$, which depends on the plasma frequency and the laser frequency, ω_0.[1] In a focused laser beam with a Gaussian spatial profile the intensity dependent γ factor makes the index of refraction highest in the center of the beam, and decreasing radially outwards. The plasma will thus act as a positive lens. For a given n_e, a critical power exists for which the relativistic self-focusing effect balances diffraction, and a channel can be formed. This critical power is given by $P_c = 17\times(\omega_0/\omega_{p0})^2$ (GW), where ω_{p0} is the plasma frequency of the ambient plasma $(\gamma=1)$.[7] The formation of relativistic channels has been observed in several experiments (see, e.g., Refs. 1, 8 and 9). Wagner *et al.* found that the channel length increases with increased laser energy (increased P/P_c).[1] Gahn *et al.* report that higher electron densities (i.e., increased P/P_c through reduced P_c) also leads to longer channels. However, this increase in length saturates at some given density and is even reduced at very high densities.[8] This decrease in length at very high electron densities is attributed to the higher energy losses due to electron heating. The ratio P/P_c can also be varied by changing the laser-pulse duration, without altering the laser pulse energy or the plasma density. It has been theoretically argued that laser pulses shorter than a plasma period should be only weakly relativistically guided, even for large ratios P/P_c.[7,10–12] However, our investigations have been performed in a regime where the laser pulse is longer than a plasma period and they constitute new experimental evidence for the influence of the pulse duration on the channel formation.

II. EXPERIMENTAL SETUP AND METHODS

The experiment presented in this report is performed with the 10 Hz multi-terawatt femtosecond laser at the Lund Laser Centre. It is a Ti:s system based on the CPA technique, operating at 800 nm. From the laser pulse compressor and onwards, the beam propagates in vacuum. The experimental setup is illustrated in Fig. 1.

The pulse duration is varied between 50 fs and 300 fs by translating one of the gratings in the compressor, and measured by second order autocorrelation in a thin potassium dihydrogen phosphate (KDP) crystal. Displacing one grating

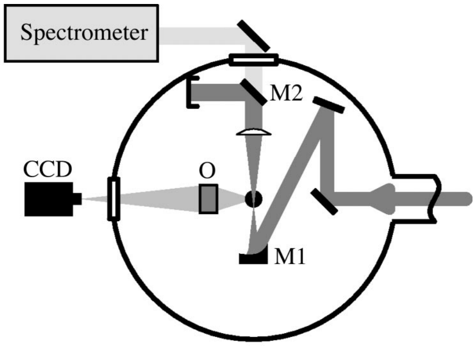

FIG. 1. The experimental setup with the side-scattering imaging system and the diagnostics for forward Raman scattered light. The laser enters from the right and is focused by an off-axis parabolic mirror, M1, into the gas jet. The channels formed are imaged onto a CCD chip using an objective, O. After the gas jet, laser radiation at the fundamental laser wavelength is reflected by a dielectric mirror, M2, to a beam-dump, while forward Raman scattered light is transmitted through M2 to a spectrometer outside the vacuum chamber.

from its normal position (optimized for minimum pulse duration) introduces a frequency modulation (chirp) in the laser pulse. The relative change, $\Delta\omega/\omega_0$, is, however, small and is not expected to significantly affect the experiment. (This is confirmed by changing between a positive and a negative chirp in the studies presented below, yielding identical results.) The horizontally polarized laser beam is apertured to 44 mm diameter and focused by a 15 cm focal length, silver-coated, off-axis parabolic mirror. In order to study the size and the shape of the laser focus it is magnified and imaged with an eight bit dynamic-range beam profiler. It is estimated that 80% of the pulse energy form a Gaussian-shaped focal spot with the radius $r_0 = 2.8\ \mu\text{m}$ at $1/e^2$ of the peak intensity, whereas 20% of the energy is spread out over a much larger area. Thus, the Rayleigh range is approximately 30 μm and the maximum peak intensity exceeds 10^{19} W/cm^2.

The focus is located at the edge of a freely expanding gas jet, 200 μm below the orifice of a pulsed valve. The orifice has a diameter of 0.5 mm, and the valve is backed with helium gas of up to 50 bar pressure. To obtain a good vacuum ($<6\times10^{-6}$ mbar) in the experimental chamber and the pulse compressor prior to each laser shot, the repetition rate in the experiment is limited to 0.2 Hz.

To allow an estimation of the electron density at different backing pressures, the frequency of the forward Raman scattered light is measured. This light appears in the spectrum of the laser pulse, after passing through the plasma, as peaks frequency-shifted from ω_0 by integer multiples of the plasma frequency. To suppress the very intense radiation at the laser frequency, a dielectric mirror designed for reflection at 800 nm, is placed in the beam before the spectral measurement (see Fig. 1). The Raman shifted light, transmitted through this mirror, is collected with a lens and sent to a grating spectrometer. The electron density is found to vary linearly with the backing pressure in the region investigated, between $n_e = 4\times10^{19}$ cm^{-3} and 2×10^{20} cm^{-3}. The positions of the Raman peaks are independent of the pulse duration, but they are more distinct and better resolved when long pulses are used.

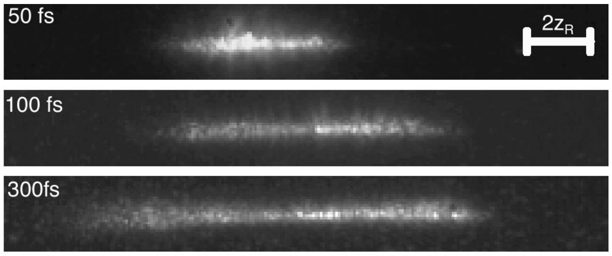

FIG. 2. Typical single-shot side images of 3 different channels, obtained with the same laser energy and plasma density, but with different pulse durations. From top to bottom; 50, 100 and 300 fs, respectively.

An objective with 13.5 cm focal length is used to collect the side-scattered light and to project an image of the interaction region (the channel) onto the chip of a charge-coupled device (CCD) camera. The spatial resolution of the imaging system is about 5 μm. Typical images are shown in Fig. 2. Some of the measurements are performed with a bandpass interference filter, centered at 800 nm, placed before the camera. With this filter, the intensities and the width of the channel images decreases slightly, but the measured channel lengths are not affected. For each set of experimental parameters, 30 images are recorded in order to allow a statistical analysis of the channel lengths. Channel formation through whole beam self-focusing or through the formation of several filaments cannot be differentiated from these images. A ‘‘channel,’’ as discussed in this report, may consequently consist of one or several filaments.

III. EXPERIMENTAL RESULTS

First, the length of the channels is found to increase with laser energy. This is in agreement with previous observations (see, e.g., Ref. 1). The growth of the channel as the ratio P/P_c increases, due to increasing pulse energy, is illustrated for three different pulse durations in Fig. 3. The electron densities are chosen so that the ratio P/P_c ranges over approximately the same values for all three curves, 1.4×10^{20} cm^{-3}, 1.1×10^{20} cm^{-3} and 0.6×10^{20} cm^{-3}, respectively. These results show that the growth-rate depends on

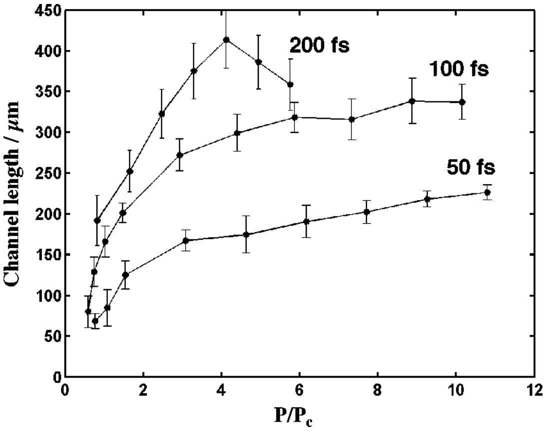

FIG. 3. Channel length versus laser pulse energy for three pulse durations and electron densities. [From top to bottom; 200 fs (1.4×10^{20} cm^{-3}), 100 fs (1.1×10^{20} cm^{-3}) and 50 fs (0.6×10^{20} cm^{-3}).]

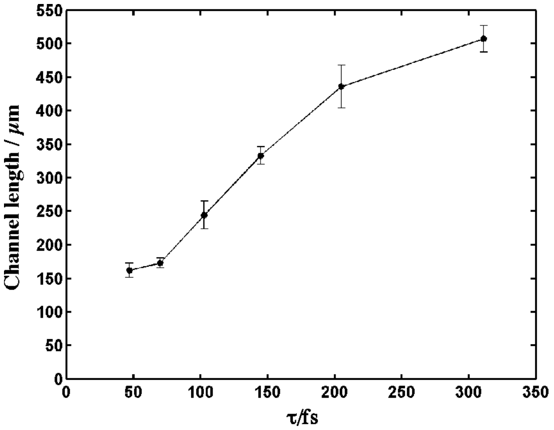

FIG. 4. The channel length increases when increasing the pulse duration while keeping $P/P_c = 3.5$ constant by increasing the pulse energy correspondingly.

the pulse duration (or density) while the onset of the channel formation does not. The curves in Fig. 3 are limited by the maximum energy available from the laser at the time of the experiment (500 mJ on target). Second, the channel length is found to increase with increasing electron densities (decreasing P_c), up to a certain point where saturation occurs. This is in agreement with the observations reported by Gahn *et al.*[8]

Next, we find that increasing the laser-pulse duration, but keeping the ratio P/P_c constant by increasing correspondingly the pulse energy (constant n_e), results in a rapid, seemingly linear, increase of the channel length with the pulse duration. This result is depicted in Fig. 4, for a plasma electron density of 1.15×10^{20} cm^{-3}. The maximum channel length is in this case limited by the diameter of the He gas jet.

Finally, the most striking result of the present study is presented in Fig. 5. It shows how the length of the relativistic channel increases with increasing pulse duration, when all other parameters are held constant. In this case, the increase in pulse duration corresponds to a *decrease* in the ratio P/P_c, from 7.0 at the shortest pulse duration to 1.1 at the longest. This remarkable increase in channel length, with reduced laser power is reproduced with several different values of laser energy and electron densities. In addition, we confirm experimentally that the observed trends are independent of the sign of the chirp of the stretched pulse.

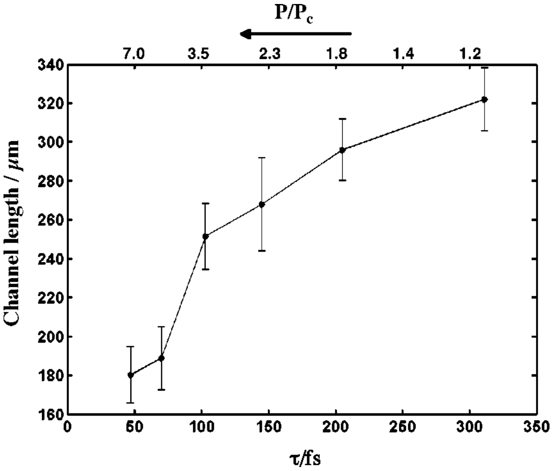

FIG. 5. The length of the channel is increasing with increasing laser pulse duration. The electron density and energy are held constant, so the increase in pulse duration corresponds to a decrease in P/P_c.

Some electrons are accelerated in the forward direction by the longitudinal plasma wave in the channel. They are detected and their kinetic energies are measured with a simple electron spectrometer consisting of a permanent magnet, giving a static magnetic field deflecting the electrons, and a scintillating screen, imaged by a CCD camera. Electrons with kinetic energies greater than 10 MeV are observed. How the total number of accelerated electrons, their kinetic energies and their spatial distribution depend on the laser pulse duration are subject to further investigations.

IV. DISCUSSION

To understand the strong influence of the laser pulse duration on the channel length, we make the following assumptions: (i) A certain amount of energy is required to form each unit of length of the plasma channel. This energy comes from the leading edge of the laser pulse, with a corresponding decrease in the remaining pulse duration. (ii) The channel formation continues, with an increase in length, until the duration of the remaining part of the pulse vanishes (becomes shorter than a plasma wavelength), or until its power drops below P_c.

To validate these assumptions, we performed three-dimensional particle-in-cell (PIC) simulations of the pulse propagating in the plasma using the code VLPL (Virtual Laser Plasma Laboratory).[13] The parameters for these simulations are chosen to mimic typical conditions in the above experiments. The results are presented in Fig. 6, where three snapshots of the optical pulse at equal time intervals (100 laser periods) are shown. They illustrate the optical pulse after it has propagated equal distances into the plasma with speed nearly the speed of light. The erosion from the leading edge of the pulse is clearly visible. Furthermore, it is seen that the pulse shortening is nearly linear with the time (dashed lines in Fig. 6).

Channel formation and pulse erosion are closely linked, and related to the electron density, the laser power and pulse duration. In order to understand qualitatively how the channel length depends on the pulse duration, we need to first study these dependencies. First, there are several contributions to the continuous energy loss from the front of the laser pulse. For example, some energy goes into setting up the quasi-static fields in the plasma, and some is lost through diffraction at the very front of the pulse (where the plasma wave has not yet been formed).[7,10–12] However, we assume that the dominating loss mechanism here is electron heating in the channel.[8] At the intensities present inside the channel ($I > 10^{18}$ W/cm^2), the mean electron kinetic energy scales as the light amplitude, i.e., $\propto\sqrt{I}$.[14] The cross section of the channel is not known exactly. However, with channeling due to relativistic and charge-displacement effects, its radius is expected to be of the order of a plasma wavelength, increasing only slowly with laser intensity.[15] For a given electron

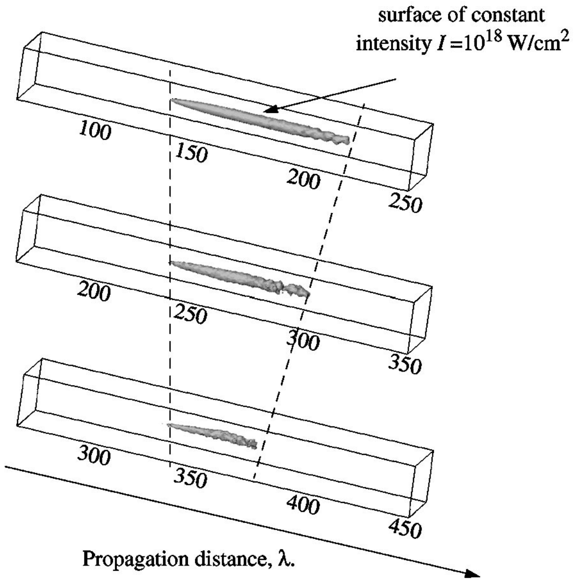

FIG. 6. The PIC code simulations of the laser pulse propagation in the plasma. The laser pulse is shown as a surface of constant intensity ($I=10^{18}$ W/cm^2) for three different times separated by 100 laser periods from each other. The propagation distance is measured in units of the laser wavelength and the dashed lines indicate the leading and trailing edge of the pulse. The simulation parameters are: $n_e=0.7\times10^{20}$ cm^{-3}, $a_0=2$, $\tau=150$ fs and $P=1.3$ TW.

density, we therefore neglect the variations in the channel cross section, and obtain an energy loss per unit length proportional to the square root of the laser power. The corresponding pulse-front erosion, or pulse shortening per unit length of the channel, then becomes inversely proportional to the square root of the laser power. This power-dependent pulse erosion, combined with the second assumption above (ii) leads to a channel length which increases linearly with time and with the square root of the laser power. A more detailed discussion should also include, e.g., charge-displacement effects. Their contribution to the channel formation is also expected to depend on the pulse duration.

With the above assumptions the trends observed can be qualitatively reproduced and understood. First, for fixed pulse duration and electron density, the channel length increases with the laser energy (or P), but not as fast as linearly, as experimentally observed (see Fig. 3). Second, with P constant, and increasing the pulse duration, a linear dependence on the pulse duration is expected, which is in good agreement with the results presented in Fig. 4 (where the highest point is limited by the extent of the gas jet). Finally, increasing the pulse duration, with all other parameters fixed, the power is reduced as $1/\tau$, so the channel length should scale as the square root of τ, until the power drops below P_c and channeling ceases. This resembles the trends obtained experimentally (Fig. 5). For each combination of pulse energy and electron density, an optimum pulse duration for the formation of long channels is therefore expected. Here we have used the full-width-at-half-maximum of the pulse envelope in time (τ_{FWHM}). However, the fraction of the pulse where the power exceeds P_c can be longer as well as shorter than τ_{FWHM}, depending on the ratio P/P_c and on the exact temporal shape of the laser pulse. This correction should be included in a more detailed analysis of the results.

In conclusion, we have shown experimentally that, for fixed pulse energy and plasma density, longer plasma channels are formed if the laser pulses are stretched in time (as long as $P>P_c$). This behavior is supported by a simple theoretical discussion. With a longer, stretched pulse the optical intensity in the channel is reduced. The pulse therefore deposits less energy per unit length to plasma heating, and the channeling extends longer.

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