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Abstract. The understanding of laser beam propagation through underdense plasmas is of vital importance to laser-plasma interaction experiments, as well as being a fundamental physics issue. Formation of plasma channels has numerous applications including table-top x-ray lasers and laser-plasma-produced particle accelerators. The fast ignitor concept, for example, requires the formation of an evacuated channel through a large, underdense plasma. Scaled experiments have shown that the axial extent of a channel formed by a 100 ps pulse is limited by the onset of the filamentation instability. We have obtained quantitative comparison between filamentation theory and experiment. More recent experiments have shown that by increasing the duration of the channel-forming pulse, the filamentation instability is overcome and the channel extent is substantially increased. This result has important implications for the fast ignitor design and the understanding of time-dependent beam dynamics.

1. INTRODUCTION

The propagation of laser beams of moderate to high intensity through fully ionized plasmas is a topic that theoretical and experimental researchers are presently trying to understand. The behavior of the beam can be modified in surprising ways by the modification of the background electron density profile by the ponderomotive force of the laser pulse and by the onset of the filamentation instability. This topic has important practical implications for inertial confinement fusion targets in which the laser beam must propagate long distances through an underdense plasma. Recently, the fast ignitor concept has been proposed, in which a laser pulse is used to clear a channel through the coronal plasma around a compressed target to provide a low density path for a high intensity laser pulse which would ignite the target fuel [1].

In this article, we will discuss recent experiments in which we have investigated the propagation of > 100 ps laser pulses through preformed fully plasmas. We have observed the formation of density channels by the ponderomotive force which, for pulse lengths of 100 ps, terminate short of the peak density due to the onset of the filamentation instability. The axial extent of the channel can be substantially increased by increasing the laser pulse length. In addition, we can measure the peak laser intensity in the filaments by detecting the energy of the ions ejected from the filament via the ponderomotive force.

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2. EXPERIMENTAL DESCRIPTION

The experiments we will be discussing all had very similar geometry. They were performed with the Janus laser facility at Lawrence Livermore National Laboratory. The experiments used two opposing beams, one of which was used to explode a parylene (CH) foil which provided an underdense plasma for the second, 100 ps Gaussian beam to propagate through. A 0.35-µm wavelength, 50 ps probe was propagated through the target plane, perpendicular to the high energy beams, and was used for interferometry.

A sample interferogram is shown in Fig. 1. In the interferometer, the phase front of the reference beam is intentionally placed at an angle with respect to the phase front of the plasma probe beam; this produces, in the case of no plasma, a series of equally spaced fringes across the field of view. For our choice of angle between the plasma probe and reference beams, the presence of a plasma into the probe beam produces a phase shift with respect to the reference beam which shows up as a bending of the fringes to the right. On the left hand side of the target, it is possible for the plasma phase shift to nullify the background phase shift, producing an "X" fringe pattern such as is seen on the left hand side of Fig. 1. Between the "X" and the target, increasing density is indicated by fringes moving in the opposite direction.

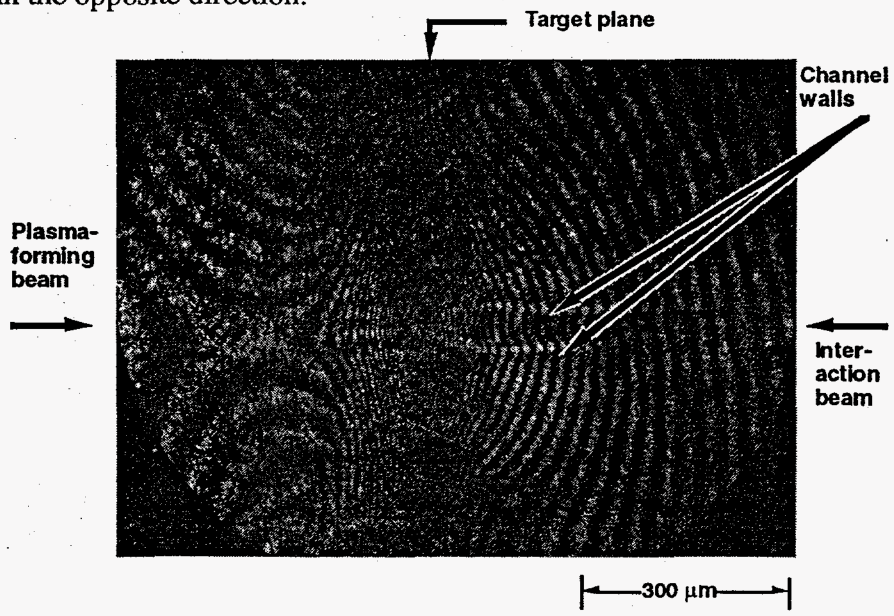

FIGURE 1. Sample interferogram which shows the density channel formed by a focused 100 ps beam propagating through a preformed plasma. Note that the channel is limited to the right hand side of the target plane where the peak density is located.

3. 100 PS RESULTS

Our initial investigations at moderate intensity (1 x 10^{15} W/cm^2) immediately showed an interesting phenomenon: the channel formed by the 100 ps pulse had a limited axial extent [2]. In these foil produced plasmas, the peak density occurs at the foil plane and has a Gaussian axial distribution.

Simulations with a modified version of the F3D code [3] that includes nonlinear motion of the ions [4] suggested that the channels were being terminated by the onset of the filamentation instability [5]. Since the instability has a preferred wavelength, it could be detected by looking at the angular distribution of the transmitted light; the angle of deflection is given by

$$\sin^{-1} \theta = k_{\perp,\max}/k_0 \tag{1}$$

where [5,6]

$$k_{\perp,\max} = (1/2)(v_o/v_e)(\omega_{pe}/\omega_0)(\omega_0/c) \tag{2}$$

and v_0 is the electron oscillatory velocity in the laser field, v_e is the electron thermal velocity, ω_{pe} is the electron plasma frequency, and ω_0 (k_0) is the frequency (wavenumber) of the incident laser.

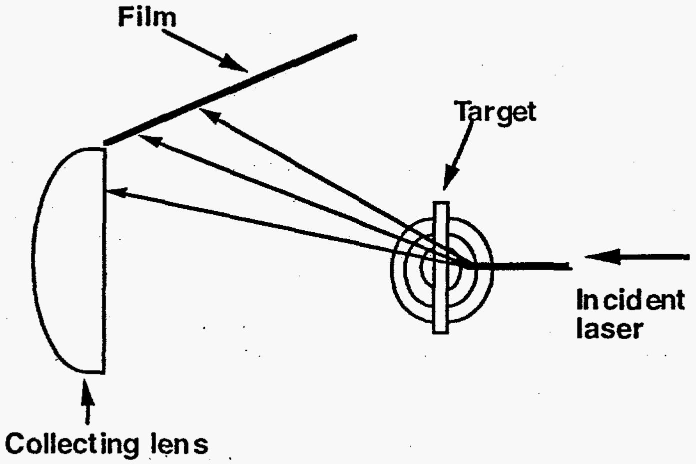

FIGURE 2. Light that is scattered by the filamentation was recorded by film which was placed outside of the collecting lens. The collecting lens was an f/2 aspheric lens which was identical to the focusing lens for the incident laser beam.

Experimentally, the deflection can be inferred by measuring the amount of the incident energy that is transmitted through the plasma within the original focusing solid angle. It can be measured directly by using film to record the pattern of the light outside the collecting lens (see Fig. 2).

The experiments confirmed the theoretical predictions. We observed a functional dependence of the deflection angle on laser intensity (see Fig. 3) and peak plasma density that agrees with Eq. (1). We also observe a corresponding decrease in the energy transmitted through the original focusing solid angle.

This observation sets a serious constraint on the fast ignitor model due to the difficulty in avoiding the filamentation instability in the coronal plasma around the ignitor target. We therefore next looked at the channel formation as a function of the input pulse width.

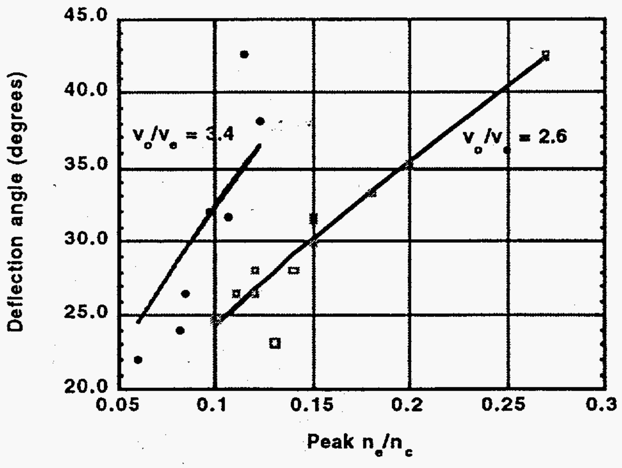

FIGURE 3. The measured deflection angle agrees well with the theoretical prediction based on the density grating set up by the filamentation instability.

4. TIME-DEPENDENT RESULTS

Figure 4 shows the transmitted energy through the collecting lens for different pulse widths [7]. For the highest allowed energies at pulse widths of 100 and 250 ps, the maximum transmission is less than 30%. If one drops the energy below the threshold, all the light goes through, although this is not compatible with the fast ignitor design. When the pulse width is increased to 500 ps, increasing the energy leads to a substantial increase in the transmitted energy. This is accompanied by an increase in the axial length of the channel.

Interferograms of the plasma taken at different times with respect to the channel forming pulse show quite clearly the evolution of the plasma. Figure 5 shows density profiles which were reconstructed from interferograms which show the plasma density distributions at times of 50 ps and 335 ps with respect to the leading edge of a 1 ns square pulse. At the earlier time, the channel is confined to the incident side of the plasma, but 300 ps later, the channel extends all the way through the plasma. This result is confirmed by LASNEX simulations and is understood in the following way. Although the laser light sprays out due to the density grating set up by the filamentation instability, there is still sufficient intensity upstream to begin to move plasma out of the beam. This takes longer, however, because the intensity is lower. Once the channel is formed, the density is too low for the filamentation instability to occur.

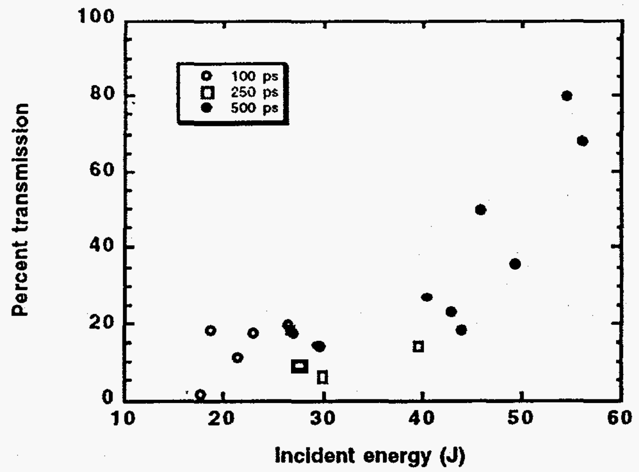

FIGURE 4. The percentage of the transmitted light collected by an f/2 lens is significantly increased when the pulse length is increased to 500 ps.

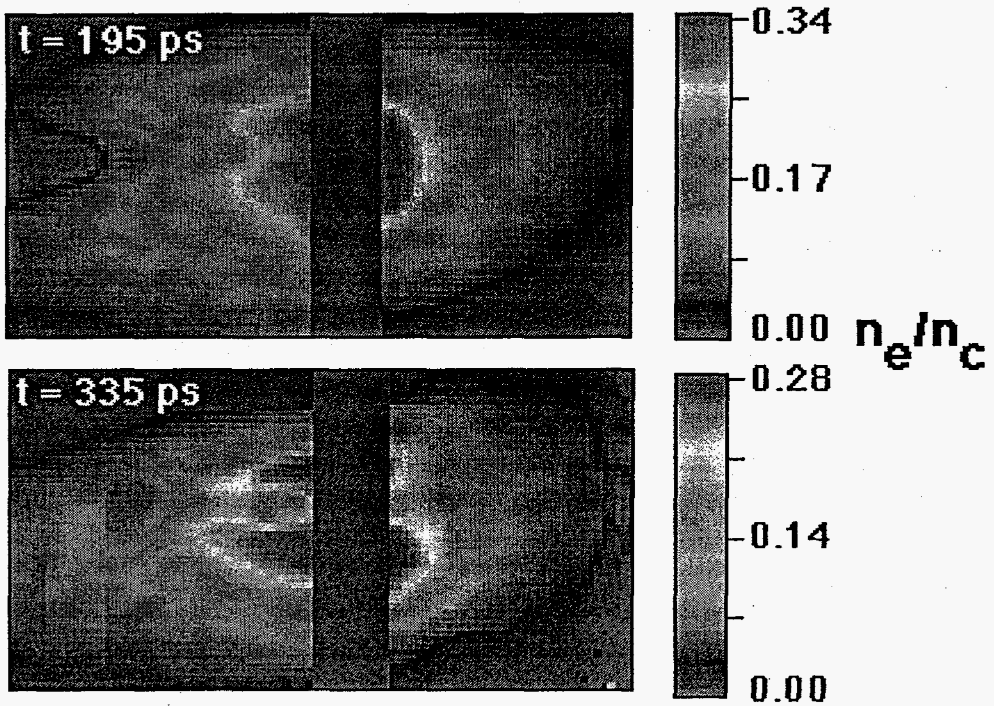

FIGURE 5. Density distributions calculated from Abel inversions of the experimental interograms. The interaction beam is incident from the left. At early times, the channel appears only on the left hand side of the target. At later times, the channel extends through the plasma.

5. FAST ION GENERATION BY FILAMENTS

The filaments that are produced by the 100 ps pulse described above can also accelerate ions to velocities which are much greater than the sound speed. A simple estimate shows the magnitude of the ion velocity that can be achieved. We equate the kinetic energy of the ion to the potential energy set up by the ponderomotive force produced by the laser pulse: $Mv^2_{max}/2 = Ze\phi = Zmv^2_{os}/4$ where M is the ion mass, m is the electron mass, ϕ is the ponderomotive potential and $v_{os} = eE/m\omega_0$ is the electron oscillatory velocity in a laser electric field E with a frequency ω_0. Solving for v_{max} gives:

$$v_{max} = (Zm/2M)^{1/2}v_{os} \qquad (3)$$

For hydrogen ($Z = 1$, $m/M = 1/1836$), and $I_L = 1.5 \times 10^{17}$ W/cm^2 (which results from the filamentation of the laser light in the plasma), we find $v_{max} = 1.7 \times 10^8$ cm/sec which corresponds to an enrgy of 15 keV; for comparison, a typical sound speed and ion temperature for these plasmas is 3×10^7 cm/sec and 500 eV, respectively.

The ion veolcities were measured at 90 degrees to the incident laser beams by a time resolved ion spectrometer [8] which used a magnetic field to separate ions of different charge-to-mass ratios. The ions pass through a collimating slit and strike a microchannel plate so that an optical streak camera can be used to measure the ion time of flight. When the interaction beam is of sufficient intensity, a high energy proton tail forms with peak energies of the order of 20 keV. These ions are sufficiently energetic to have ion-ion mean free paths which are greater than the plasma diameter (400 μm).

From Fig. 6 we see that the increase in ion energy is coincident with the onset of the filamentation instability. The onset of the filamentation instability is determined from measurements of the light transmitted through the plasma. The light from the interaction beam that is transmitted through the plasma is collected with an f/2 lens and relayed to a full aperture energy calorimeter; since the interaction beam is focused with an f/2 lens, in the absence of deflections, all the incident laser light is collected by the calorimeter with the exception of backscattered light. As we have observed earlier, the beam breaks up into filaments; the density grating set up by the filaments deflects light out of the collection solid angle, leading to a decrease in the ratio of the measured transmitted energy to the incident energy.

As the laser energy is increased, the peak ion energy first increases with the laser energy, then reaches a constant value when the peak density is 0.25nc. If the peak density is reduced to 0.15nc, the input energy has to be increased before the ion energy increases, but at 30 J, we attain the same ion energy as at the higher density.

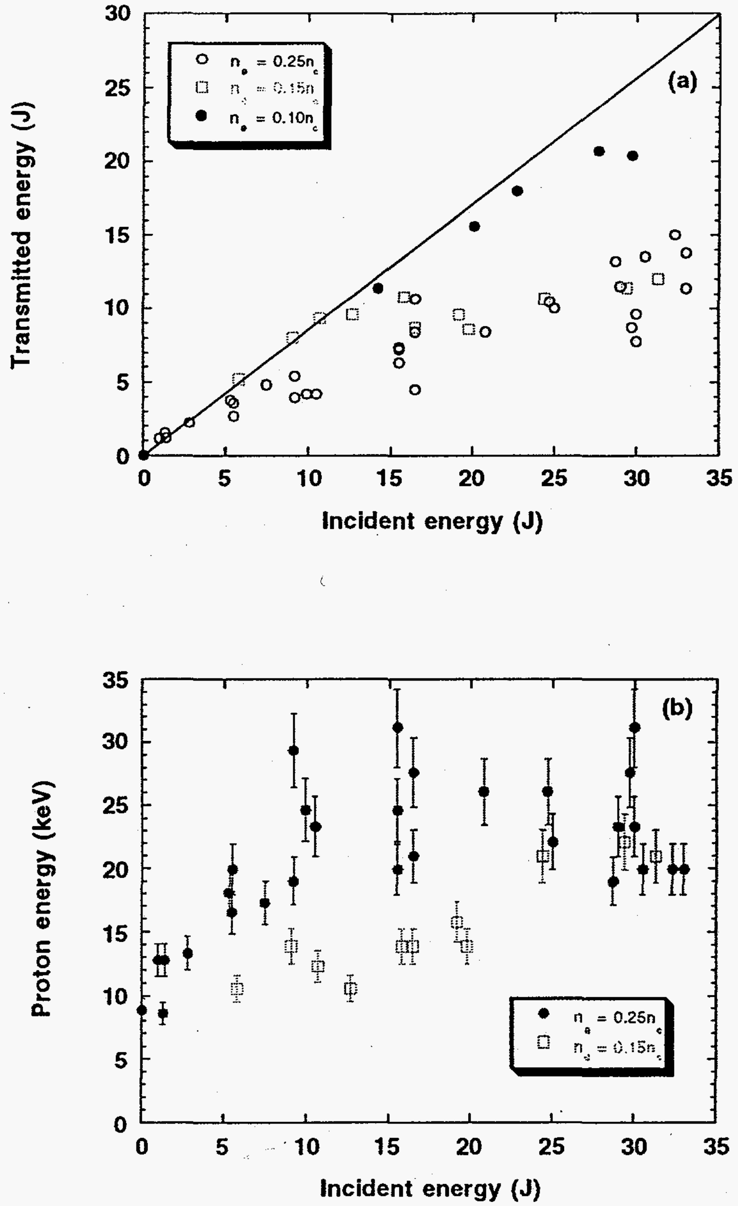

FIGURE 6. Comparison of (a) the onset of the scattering of the transmitted light due to filamentation, and (b) the increase in the peak proton energy as a function of incident energy.

In summary, we have established a versatile test bed for studying various aspects of laser propagation through fully ionized plasmas. Comparison to models, which are used to simulate the fast ignitor problem, have enabled us to validate those models and to point out the filamentation instability as an important concern. We have demonstrated that the laser pulse length is a very important parameter for propagating a laser beam through a relatively high density plasma, a result which is a necessary condition for the success of the fast ignitor concept. We have shown that the laser beam initially spreads due to filamentation, but is still of sufficient intensity to depress the plasma density and initiate a self-guiding process that, if the pulse is long enough, leads to the formation of a coherent channel.

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