Observation of Solid-Density Laminar Plasma Transparency to Intense 30 Femtosecond Laser Pulses

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Near total transmission of 30 fs laser pulses through 0.1 μm plastic foil targets has been observed for the first time at an intensity of 3×10^{18} W/cm^2 in absence of precursor plasma. This level of transmittivity is far above the level predicted by current theoretical models or numerical simulations. The transmittivity was found to drop by 40 times at an intensity of 4×10^{17} W/cm^2 and was within the experimental background level at 5×10^{16} W/cm^2. Our measurements strongly suggest a new mechanism of propagation of electromagnetic waves through overdense plasmas. [S0031-9007(97)04356-1]

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The interaction of intense optical radiation with plasmas characterized by solid-density and ultrasteep gradients can now be studied by using short pulse lasers capable of delivering up to joules of energy in few tens of femtoseconds. In principle, such laser systems open the possibility of investigating phenomena produced by high intensity radiation in experimentally unexplored conditions, including propagation in plasmas whose density is orders of magnitudes higher than the critical density $n_c = m_e \omega_0^2 / 4\pi e^2$, ω_0 being the laser frequency.

Recently, penetration of ultraintense, short laser pulses into overdense plasmas has been extensively investigated both theoretically and experimentally also in view of its relevance to the implementation of the fast ignitor concept [1]. Several effects have been considered that predict enhanced propagation, including anomalous skin effect [2], self-induced transparency [3], and hole boring [4,5]. Hole boring and self-induced transparency have been mostly investigated in the interaction of relativistic laser pulses with moderately overdense plasmas. In particular, hole boring has been proposed as a possible mechanism for deep energy deposition in overdense plasma regions due to ponderomotive forces at relativistic intensities. The importance of relativistic effects is given by the value of the normalized relativistic momentum, $a_0 = p_{os}/m_o c \cong 0.85 \lambda_0 \sqrt{I_0}$ where p_{os} is the momentum of the electrons oscillating in the laser field, m_o is the electron mass, c is the velocity of light, and I_0 and λ_0 are the laser intensity in units of 10^{18} W/cm^2 and the wavelength in microns, respectively. For these effects to give a nonmarginal increase of transmittivity through plasma slabs, either the plasma must be weakly overdense or the intensity must be very high ($a_0 \gg 1$).

At nonrelativistic intensity the propagation of the electromagnetic (e.m.) wave into an overdense plasma is expected to be limited to the skin depth δ_0. A deeper penetration (anomalous skin effect) is possible in very hot plasmas, where the electron velocity becomes larger than $\omega_0 \delta_0$ [6]. Recently the anomalous skin effect in solid-density plasmas has been considered both analytically [7] and numerically [8], with attention to the case of interaction with thin foils.

From an experimental point of view, a serious problem that can prevent interaction of short pulses with solid-density plasmas may arise from the laser prepulse originating from amplified spontaneous emission (ASE) in the laser chain. If the intensity on target due to the prepulse (typically of nanosecond duration) is higher than the threshold intensity for plasma formation on target, a precursor plasma is formed which prevents the main femtosecond pulse to interact directly with the solid. In a previous experiment [9] it was shown that the use of thin plastic foil targets may avoid formation of precursor plasma, enabling the interaction of the main femtosecond pulse with high density laminar plasmas. That experiment also provided evidence [10] of a substantial transmittivity, of the order of a few percent of the incident energy.

In this Letter we report further and novel experimental results on the transmittivity of solid-density laminar plasmas carried out using the 30 fs (Ti:sapphire) laser of the Laboratoire d'Optique Appliquée, focused onto 0.1 μm thick plastic foils. In this experiment we found that when the laser intensity on target is greater than 10^{17} W/cm^2 the transmittivity goes above the experimental background level of $\approx$1% and increases dramatically with laser intensity, approaching full transparency at an intensity of 3×10^{18} W/cm^2. To our knowledge, this is the first time that such an important observation is reported in the interaction with a laminar plasma whose sharp boundaries are made possible by the absence of prepulse effects.

The 815 nm, 30 fs laser pulse was focused on target with an $f/7.5$ off-axis parabolic mirror, with an angle of incidence on target of 20°. The laser pulse was linearly P-polarized. The focal spot was 10 μm in diameter.

The intensity was varied between 5×10^{16} W/cm^2 and 3×10^{18} W/cm^2, by varying the energy in the pulse. The transmitted pulse was studied by using a diffusing screen placed beyond the target, on the laser propagation direction, at a distance of 1.8 times the focal length of the focusing optics. A demagnified image of the screen was formed onto a CCD array and onto the entrance slit of a spectrometer. A second CCD array was placed on the output focal plane of the spectrometer. An additional CCD imaging channel was set up on the specular reflection direction, with the object plane located at the target plane.

The laser system used in our experiment is characterized by an ASE lasting approximately 10 ns that forms a "pedestal" to the main pulse. The measured contrast ratio, i.e., the ratio between the power delivered in the fs pulse and that delivered in the ASE, was $\geq 10^7$. A severe test on the effect of the ASE on target was performed by firing the laser system, but without injecting the fs pulse in the amplifier chain. In this condition, we observed no damage on target over the whole range of ASE intensities. In contrast, when the fs pulse was fired, a ≈ 100 μm diameter hole was produced in the foil. This test is, for two distinct reasons, a proof "*a fortiori*" that in full shots the target does not explode before the arrival of the femtosecond pulse. First, since no energy is spent in the amplification of the fs pulse, the level of ASE is greater than in the case of operation with fs pulse injection. Second, only the leading part of the ASE pulse prior to the arrival of the main fs pulse is relevant in determining the interaction conditions of the main pulse. On the other hand, within the explored range of intensity of the main 30 fs pulse, a nearly instantaneous ionization of the target material (FORMVAR: $C_5H_{11}O_2$) is expected to occur. In this sense, even though direct electron density measurements have not been carried out, we can state that the results presented here refer to interaction with a solid-density laminar plasma.

The transmittivity as a function of the incident laser intensity is presented in the plot of Fig. 1. Each data point was obtained by taking into account several interaction events for each laser intensity and by averaging the results. The background line reported on the graph indicates the level at which the transmitted energy is comparable with the ASE energy (close to 1% of the main pulse energy), and consequently measurements below this level cannot be entirely related to the main pulse. According to the plot of Fig. 1, the transmitted fraction at incident intensities below 10^{17} W/cm^2 lies within the experimental background level. However, as the incident intensity increases, the transmitted fraction increases dramatically and the target becomes basically transparent at 3×10^{18} W/cm^2.

The diffusing screen also gave information on the intensity distribution in the near field beyond the focus. A typical example of such data is shown in Figs. 2(a) and 2(b), where the cross section of the transmitted pulse 2(b) at a laser intensity on target of 3×10^{18} W/cm^2 is

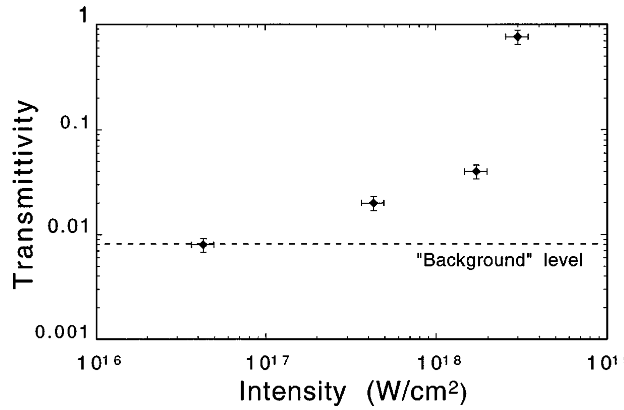

FIG. 1. Transmittivity as a function of the intensity of the 30 fs laser pulse incident on 0.1 μm thick plastic target. The background level indicates the level at which the energy in the pedestal (ASE) is comparable with the transmitted energy.

compared with that taken without the target 2(a) at the same intensity. The three perpendicular lines visible on the images are spatial calibration markers placed on the diffusing screen. A preliminary survey of these results shows that the pulse transmitted through the foil does not suffer major changes. The angular spread appears slightly reduced after interaction with respect to the case of free propagation while the transmitted intensity pattern is elongated in the horizontal direction.

Very interesting is the comparative spatial Fourier analysis of these patterns with and without the target. The square root of the intensity distribution of the images taken by the diffusing screen, i.e., a quantity proportional to the electric field in the near field, was Fourier transformed using a two-dimensional fast Fourier transform algorithm. The square of the modulus of the Fourier transform distribution was then calculated. Within the paraxial approximation, and with appropriate assumption on the phase, we obtain the intensity distribution of the laser light in the far field, i.e., on target. The calculation has been performed for both patterns 2(a) and 2(b), and the logarithm of the results are shown in Figs. 2(c) and 2(d).

The intensity distributions in the near field of the transmitted pulses without and with the target were normalized to the corresponding average transmitted intensities, i.e., 1 and 0.76, in order to allow a direct quantitative comparison of the results. Some high frequency spatial modes are present in the far field image 2(c) obtained from the near field image 2(a) of the free propagating pulse. The modulations (rings) are likely to be due to a sharp radial cut in the amplification/compression chain of the laser system. The far field image of 2(d), obtained from the near field image 2(b) taken when interaction with the target occurred, shows that those high spatial frequency modes are basically suppressed by the interaction with the target. In other words, the interaction acts as a spatial filter for the high intensity ultrashort laser pulse. Further evidence of this observation is given by the images taken on the reflection channel.

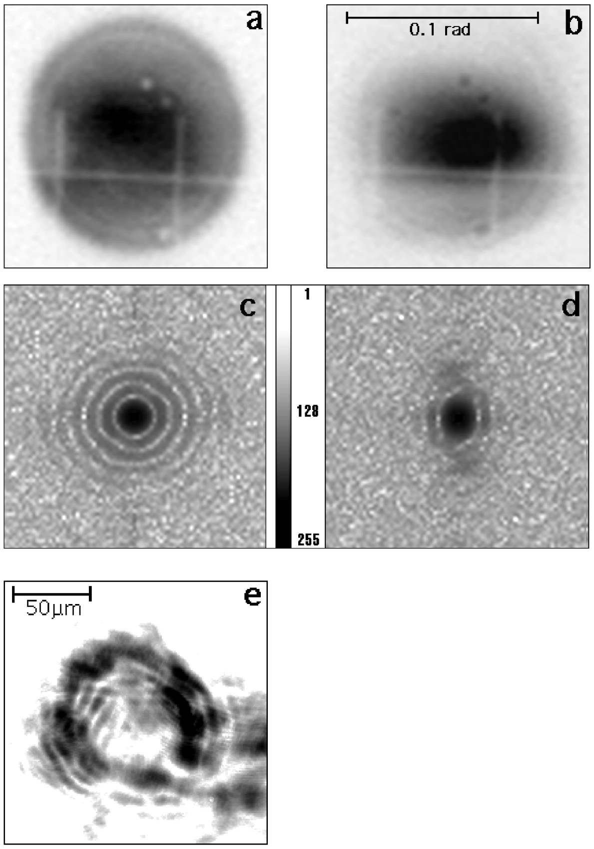

FIG. 2. (a) and (b): Images of the cross section of the transmitted pulse without (a) and with (b) the 0.1 μm thick plastic target taken with the diffusing screen at an intensity in the focal plane of 3×10^{18} W/cm^2. (c) and (d): Two-dimensional fast Fourier transform of the pulse cross sections of patterns (a) and (b), i.e., without (c) and with (d) the target, respectively. The logarithm of the modulus of the Fourier transforms are shown as gray scale images. (e) Image taken on the reflection channel with the object plane located at the target plane. A similar pattern is obtained by subtraction of the pattern (d) from the pattern (c).

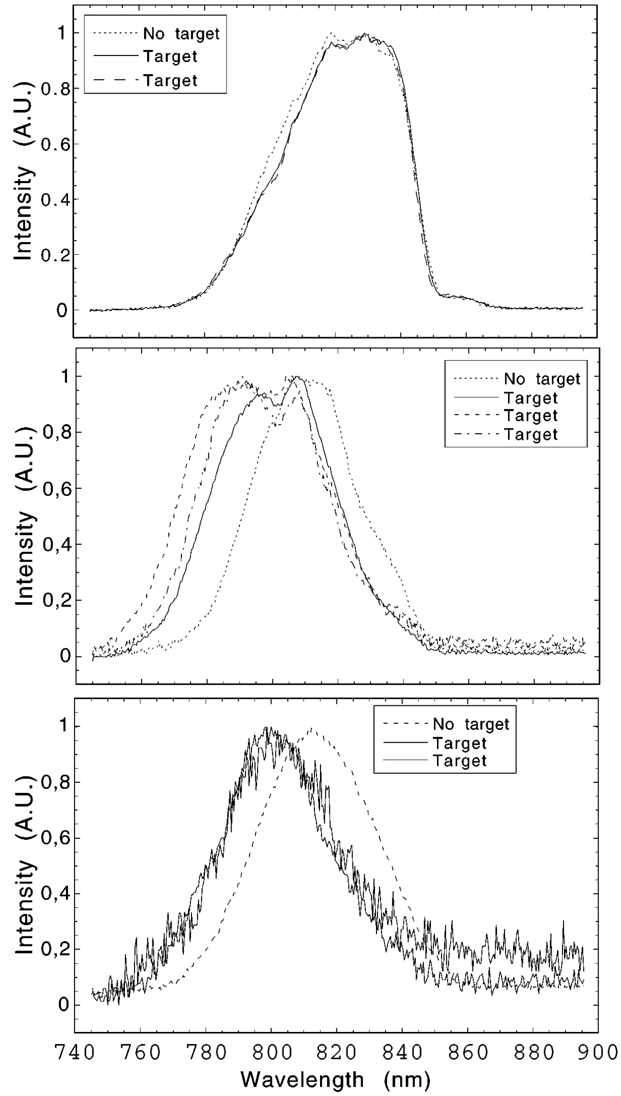

FIG. 3. Space resolved spectra of the transmitted pulse at three different intensities on target, 3×10^{18} W/cm^2 (upper), 4×10^{17} W/cm^2 (middle), and 5×10^{16} W/cm^2 (lower). The unperturbed laser spectrum (dotted line) obtained without the target at each laser intensity is also plotted for comparison.

The image of Fig. 2(e) shows a CCD image of the reflecting region of the target that is also the far field of the pulse. It shows that reflection occurs mainly from a region of the target well outside the main spot ($\approx$10 μm diameter) and the reflected pattern has a ringlike shape. By comparing the Fourier transform patterns 2(c) and 2(d) with each other, we can conclude that the pattern of Fig. 2(e) is generated by the outer rings in the far field pattern of the incident pulse (filtered out from the transmitted pulse) that is specularly reflected by the target surface.

Also interesting is the comparison between the spectra of the freely propagating pulse and those of interacted pulses at different pulse energies, as shown in Fig. 3. The spectral bandwidth of the pulse is close to the Fourier limit for a pulse with a 30 fs FWHM Gaussian temporal profile. In agreement with the expected performance of the laser system, these spectra also show a redshift when the entire amplification chain is fired.

The comparative analysis shows that the interaction process produces blueshift at moderate and intermediate intensities, while producing no shift at high intensity. In this latter case the bandwidth is also unaffected by the interaction. The spectral properties of the transmitted pulse were found to be stable shot to shot, except at intermediate intensity (4×10^{17} W/cm^2) where shot to shot variations in shift and width were observed.

Within the entire intensity range explored the target foil is expected to be ionized during the pulse. In fact, at the lower and intermediate intensity the blueshift in the spectrum of the transmitted pulse is a clear signature of ultrafast ionization. This is well supported also by the amount of the blueshift, which is about 13 nm at 5×10^{16} W/cm^2, and about 20 nm at 4×10^{17} W/cm^2.

If we assume that the frequency shift $\delta\omega$ is due to self-phase modulation of the laser pulse, i.e., to the ultrafast decrease of the refractive index due to the laser induced ionization, we have [11]

$$\delta\omega = -(L/c)(\triangle\mu/\triangle t)\omega_0 . \quad (1)$$

Considering a change of the refractive index $\triangle\mu \approx -1$ as that due to a transition from zero electron density to the critical density, we can use Eq. (1) to evaluate the time scale $\triangle t$ of such a transition. By taking the interaction path equal to the foil thickness $L = 0.1$ μm, we find $\triangle t \approx 20$ fs and $\triangle t \approx 13$ fs for the low and intermediate intensity, respectively. These values are fully consistent with the rise time of the laser pulse. The consistency strongly supports the assumption that ultrafast ionization occurs and provides indirect evidence that the plasma thickness is indeed comparable to the original foil thickness. The absence of shift in conditions close to the full transparency at 3×10^{18} W/cm^2 suggests that, in this case, ionization involves a negligible portion of the pulse.

The transparency is observed at an intensity of 3×10^{18} W/cm^2 value at which $a_0 \cong 1.2$. As the intensity is only weakly relativistic, and ponderomotive force effects are prevented by enormous electrostatic restoring forces, self-induced transparency and hole boring are ruled out.

If we consider in turn the anomalous skin effect, the numerical simulations of Ref. [8] show that the fraction of energy transmitted by a 0.1 μm thick plasma is expected to be within the range of 10^{-5} to 10^{-6}, i.e., many orders of magnitude lower than the transmittivity measured in our experiment at 3×10^{18} W/cm^2.

To our knowledge, no theoretical models or numerical simulations reported so far can explain our observations. It seems that we are facing a novel effect which certainly depends upon laser intensity but may be enhanced by the extremely short duration of the laser pulse.

Very recently, the effect of strong static magnetic fields has been taken into account [12] in the interaction of intense electric fields with electrons. Preliminary calculations on this model show that for magnetic fields of the order of hundreds of MG the motion of electrons along the oscillating field is strongly inhibited and the e.m. wave propagates basically unperturbed. On the other hand, because of the physical properties of our target and to the ultrashort pulse duration of 30 fs, highly transient volume ionization may occur in our experimental conditions as indicated by the shifts observed in the spectra of Fig. 3. Fast ionization and consequent generation of large currents in the thin layer of material may provide the conditions for production of the sufficiently intense quasistatic magnetic fields necessary to enable transparency.

In conclusion, we studied the propagation of intense 30 fs laser pulses through 0.1 μm plastic targets. Our measurements show that solid-density plasma transparency takes place at an intensity of 3×10^{18} W/cm^2. These results suggest that a completely new mechanism of propagation of an e.m. wave through a highly overdense plasma is taking place, distinct from other observed or proposed effects like anomalous skin effect, ponderomotive hole boring, and relativistic self-induced transparency. We also observed that in the transmitted pulse some high frequency spatial modes generated by the amplifier chain were filtered out by selective reflection on target. This latter effect provides a novel and simple way to perform a difficult task like the spatial filtering of high intensity, ultrashort, aberrated laser pulses. In our opinion, the observation of transparency of solid-density plasmas to ultrashort pulses at intensities corresponding to $a_0 \cong 1.2$ opens a completely new area of investigation, very promising for applications like the fast ignitor scheme, and challenging for theoretical plasma physics.

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[1] M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E. M. Campbell, M. D. Perry, and R. J. Mason, Phys. Plasmas **1**, 1626 (1994).
[2] W. Rozmus and V. Tikhonchuk, Phys. Rev. A **42**, 7401 (1990).
[3] E. Lefebvre and G. Bonnaud, Phys. Rev. Lett. **74**, 2002 (1995).
[4] S. C. Wilks, W. L. Kruer, M. Tabak, and A. B. Langdon, Phys. Rev. Lett. **69**, 1383 (1992); R. Kodama, K. Takanashi, K. A. Tanaka, M. Tsukamoto, H. Hashimoto, Y. Kato, and K. Mima, Phys. Rev. Lett. **77**, 4906 (1996).
[5] G. Malka and J. L. Miquel, Phys. Rev. Lett. **77**, 75 (1996).
[6] E. S. Weibel, Phys. Fluids **10**, 741 (1967).
[7] G. Ma and W. Tan, Phys. Plamas **3**, 349 (1996).
[8] J. P. Matte and K. Aguenou, Phys. Rev. A **45**, 2558 (1992).
[9] L. A. Gizzi, D. Giulietti, A. Giulietti, P. Audebert, S. Bastiani, J. P. Geindre, and A. Mysyrovicz, Phys. Rev. Lett. **76**, 2278 (1996).
[10] D. Giulietti, L. A. Gizzi, V. Biancalana, T. Ceccotti, P. Audebert, J. P. Geindre, and A. Mysyrovicz, in *Ultrafast Processes in Spectroscopy,* edited by O. Svelto *et al.* (Plenum Press, New York, 1996), p. 331.
[11] D. Giulietti, V. Biancalana, M. Borghesi, P. Chessa, A. Giulietti, and E. Schifano, Opt. Commun. **106**, 52 (1994).
[12] D. Teychenné, D. Giulietti, A. Giulietti, and L. A. Gizzi (to be published).