HIGH INTENSITY FEMTOSECOND LASER INTERACTIONS WITH THIN FILMS

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Abstract. We present the results of an experimental investigation on the interaction of high intensity 30 femtosecond laser pulses with very thin plastic foil targets. Transmittivity measurements show that, in absence of precursor plasma, near total transmission through 0.1μm foil targets occurs at an intensity of 3×10^{18} W/cm^2. This level of transmittivity is well above the predictions of current theoretical models or numerical simulations. The transmittivity drops by 40 times at an intensity of 4×10^{17} W/cm^2 and goes within the experimental background level at 5×10^{16} W/cm^2. Spatial filtering of the intense transmitted pulse was observed. An ionisation timescale of ≈10 fs is inferred by the measured blue-shift of the transmitted pulse. Finally, hard X-ray emission is detected at the maximum laser intensity level.

INTRODUCTION

A new class of laser-plasma interaction experiments can now be performed by using the latest generation of 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 fundamental physical processes produced by high intensity radiation in experimentally unexplored conditions. Among the possible effects predicted in this regime, particular attention is being devoted to the propagation in plasmas whose density is higher than the critical density $n_c = m_e\omega_o^2/4\pi e^2$, ω_o being the laser frequency. Recently, penetration of ultra-intense, short laser pulses in overdense plasmas has been extensively investigated both theoretically and experimentally also in view of their relevance in the implementation the fast ignitor concept. Several effects have been considered that predict enhanced propagation, including anomalous skin effect [1], self induced transparency [2], hole boring[3] driven by ponderomotive forces. Production of energetic electrons predicted in these interaction conditions has in fact been observed experimentally [4].

Hole boring and self-induced transparency have been mostly investigated for density higher than but comparable with n_c. Self-induced transparency takes into account a plasma that is "classically opaque" at ω_o, but becomes transparent due to the increased effective mass of electrons oscillating in the laser field at relativistic velocities. Such a relativistic effect is expected to be important when $a_o >> 1$, where $a_o = 0.85\lambda_o I_o^{1/2}$ is the normalised relativistic momentum of quivering

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electrons, I_o and λ_o being the laser intensity in units of 10^{18} W/cm^2 and the wavelength in microns, respectively.

At non-relativistic intensities the propagation of the e.m.wave into an overdense plasma is expected to be limited to the skin depth δ_o as an evanescent wave. A deeper penetration (anomalous skin effect) is possible in very hot plasmas, where the thermal velocity of electrons v_{th} becomes larger than $\omega_o \delta_o$. In this condition electrons may travel over a distance larger than the normal skin depth, and consequently the conductivity becomes non local. A description of this process in plasmas has been given by Weibel [5]. Recently the anomalous skin-effect in solid-density plasmas has been considered both analytically [6] and numerically [7], with attention to the case of interaction with thin foils and taking into account the dependence of the collision frequency upon electron velocity. The transmittivity of thin foils in this anomalous regime is predicted to be substantially higher than the in the case of normal skin effect. It is interesting to note that the simulation conditions of Ref.7 are very close to the ones of our experiment. Another important aspect under investigation is the ultra-fast ionisation occurring in the interaction of intense femtosecond pulses with solids.

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 amplifier chain. If the intensity on target due to the prepulse (typically of nanosecond duration) is higher than the threshold intensity for plasma formation on the target, a precursor plasma is formed which prevents the main femtosecond pulse to interact directly with the solid.

In a previous experiment [8] it was shown that the use of targets consisting of thin plastic foils may avoid formation of precursor plasma, enabling the interaction of the main femtosecond pulse with high density laminar plasmas characterised by ultra steep gradients. This features allowed a correlation between second harmonic emission and hard X-ray emission to be studied as a function of laser polarisation, in the interaction of 150fs laser pulses at an intensity of 5×10^{17} W/cm^2, with a steep gradient laminar plasma originating from a 0.08μm thick plastic foil. That experiment also provided evidence [9] of a substantial transmittivity, of the order of 5% of the incident energy, through the foil.

In this paper we report further and novel experimental results on the interaction of 30fs laser pulses delivered by the Ti:Sapphire system of the Laboratoire d'Optique Appliquée, focused onto 0.1μm thick plastic foils. The post surprising results concern transmittivity measurements. 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 ≈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 pre-pulse effects.

An outline of the experimental set up is reported below, followed by a detailed description of the experimental results including transmittivity as a function of the incident laser intensity, evidence of spatial filtering of the intense pulse and ultra-fast ionisation rate measurements. Finally, our experimental results are summarised and compared with the predictions of current theoretical models in our experimental conditions.

THE EXPERIMENT

The 815nm, 30fs laser pulse was focused f/7.5 onto a 0.1μm thick plastic foil target, using an off-axis parabolic mirror, with an angle of incidence on target of 20 degrees. The laser pulse was linearly polarised with the electric field in the plane of incidence (*P*- polarised). The focal spot was 10μm 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 1.8 times the focal length of the focusing optics. A demagnified image of the screen was formed onto a CCD array and on 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. In addition, we monitored the soft X-ray emission (≈1-10keV) by means of a PIN diode and the hard X-ray yield (up to several MeV) by using NaI(Tl) crystal scintillators, coupled to photomultiplier tubes. Both X-ray detectors were placed to look at the radiation emitted backward.

Prepulse test

The laser system used in our experiment is characterised by an ASE lasting approximately 10ns 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. 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. Firstly, 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. Secondly, 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. Atomic excitation and partial ionisation in the target due to ASE cannot be excluded, but we are highly confident that there is no long scale-length plasma formation in front of the target prior to the high power pulse impact. So, we can state that the measurements shown in this letter are the actual result of interaction of the short pulse with the unexploded foil. On the other hand, within the explored range of intensity of the main 30fs pulse, a nearly instantaneous full ionisation 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 conclude that the results presented here refer to interaction with a solid-density $\approx 5\times10^{23}cm^{-3}$ laminar plasma.

Transmittivity vs. laser intensity

The dependence of 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 error bar was estimated by the standard deviation of the set of data considered. 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 below this level the measurements 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.

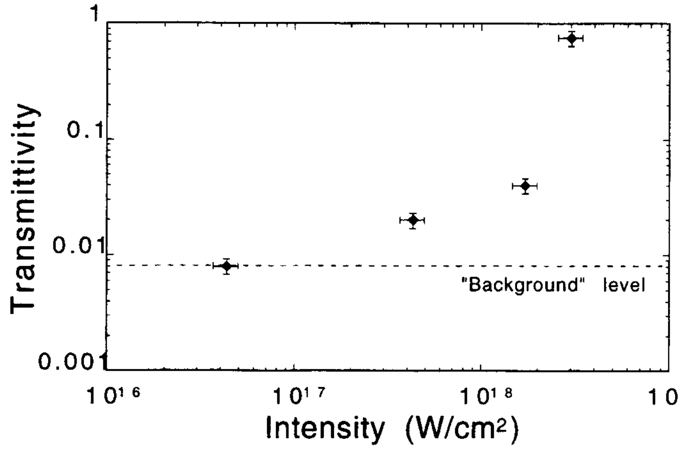

FIGURE 1. Transmittivity as a function of the intensity of the 30fs laser pulse incident on 0.1μm thick plastic target. The background level indicates the level at which the energy in the pedestal (ASE) is comparable with the transmitted energy

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 Fig.2(a) and (b), where the cross section of the transmitted pulse (b) at a laser intensity on target of 3×10^{18} W/cm^2 is compared with that taken without the target (a) at the same intensity.

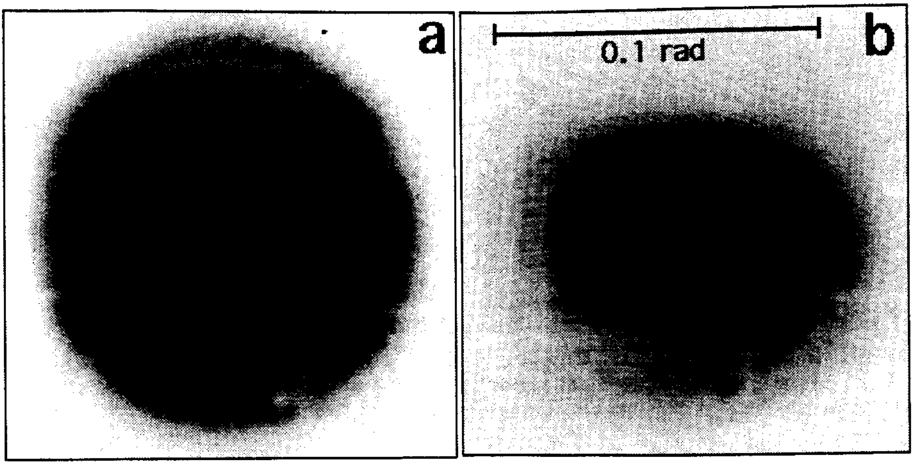

FIGURE 2.(a) and (b) - Images of the cross section of the transmitted pulse without (a) and with (b) the 0.1μm target taken with the diffusing screen at an intensity in the focal plane of 3×10^{18} W/cm^2.

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.

Fourier analysis: spatial filtering

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 2-dimensional FFT 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 (a) and (b) and the logarithm of the results are shown as grey scale plots in Fig.2(c) and (d).

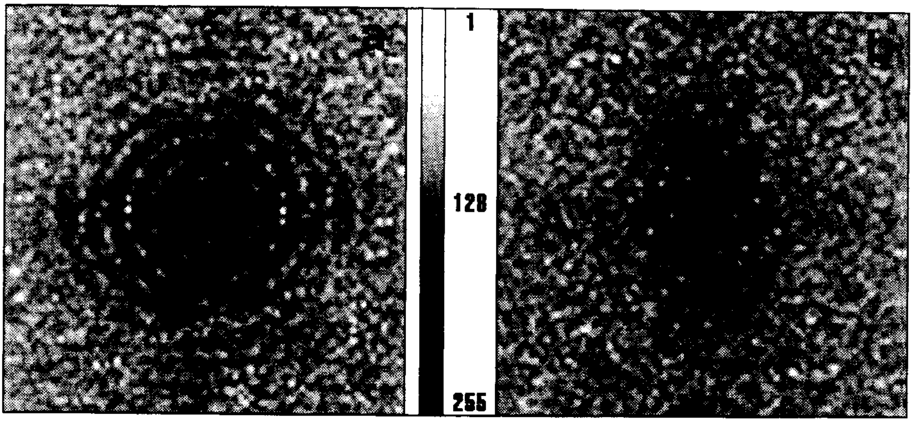

FIGURE 3. (a) and (b) - Two-dimensional fast Fourier transform of the pulse cross sections of the patterns of Fig.2 (a) and (b), i.e. without and with the target respectively. The logarithm of the modulus of the Fourier transform is shown as a grey-scale image.

The intensity distributions in the near field of the transmitted pulses without and with the target were normalised 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 of Fig.3(a) obtained from the near field image of Fig.2(a) of the free propagating pulse.

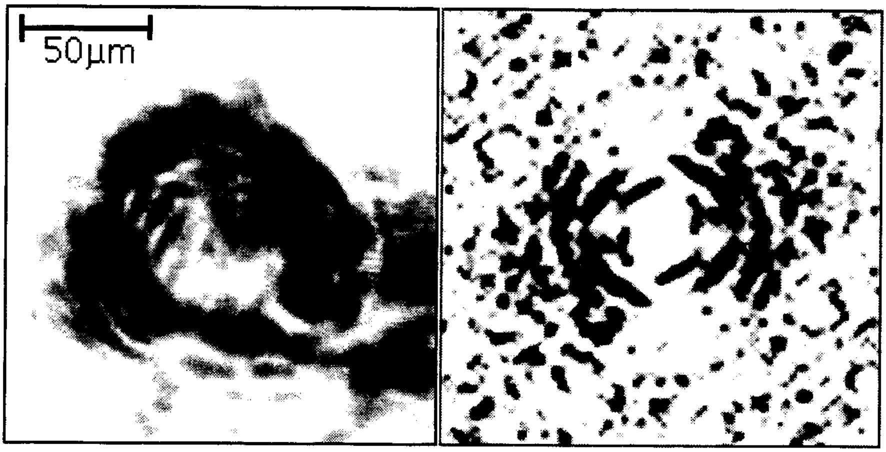

FIGURE 4. (left) Image taken on the reflection channel with the object plane located at the target plane. A similar pattern (right) is obtained by subtraction of the pattern of Fig. 3(a) from the pattern of Fig.3(b).

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 Fig.3(b), obtained from the near field image Fig.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 ultra-short laser pulse. Further evidence of this observation is given by the imagestaken on the reflection channel. The image of Fig.4 shows an 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 (≈10μm diameter) and the reflected pattern has a ring-like shape. By comparing the Fourier transform patterns of Fig.3(c) and (d) with each other, we can conclude that the pattern of Fig.4 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.

Spectral analysis: ultra-fast ionisation

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.5. The spectra of the pulse without target and diffused by the screen at the three energy levels are shown in each graph as dotted lines. The spectral bandwidth of the pulse is close to the Fourier limit for a pulse with a 30fs FWHM gaussian temporal profile. In agreement with the expected performance of the laser system, these spectra also show a red shift when the entire amplification chain is fired.

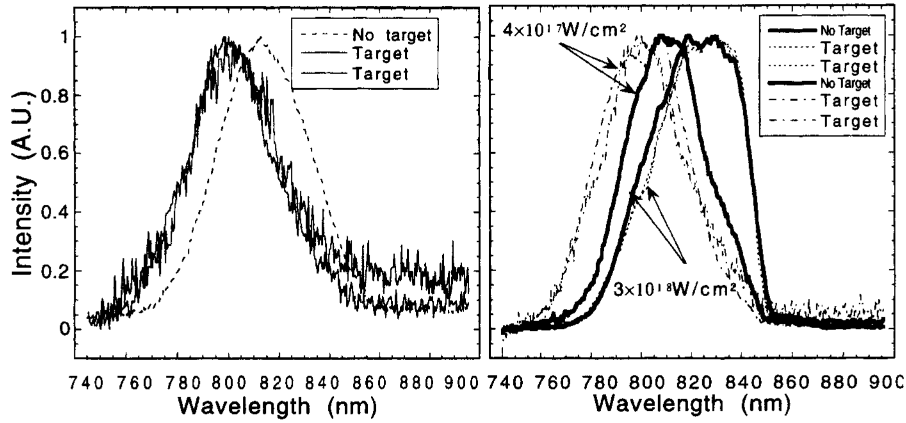

FIGURE 5. Space resolved spectra of the transmitted pulse at three different intensities on target, 3×10^{18} W/cm^2 (upper), 4×10^{17}W/cm^2 (middle) and 5×10^{16} W/cm^2 (lower). The unperturbed laser spectrum (dotted line) obtained without the target at each laser intensity is also plotted for comparison.

The comparative analysis shows that the interaction process produces a clear blue shift at moderate and intermediate intensities. The spectrum of the pulse transmitted at the higher intensity considered here suffers only a minor perturbation while the whole bandwidth is basically unaffected. The spectral properties of the transmitted pulse were found to be stable shot to shot, except at the intermediate intensity (4×10^{17} W/cm^2) were shot to shot variations in shift and width were observed. Another important observation on the dependence of ionisation timescale upon the laser intensity can be made by taking into account space-resolved measurements as presented in Fig.6.

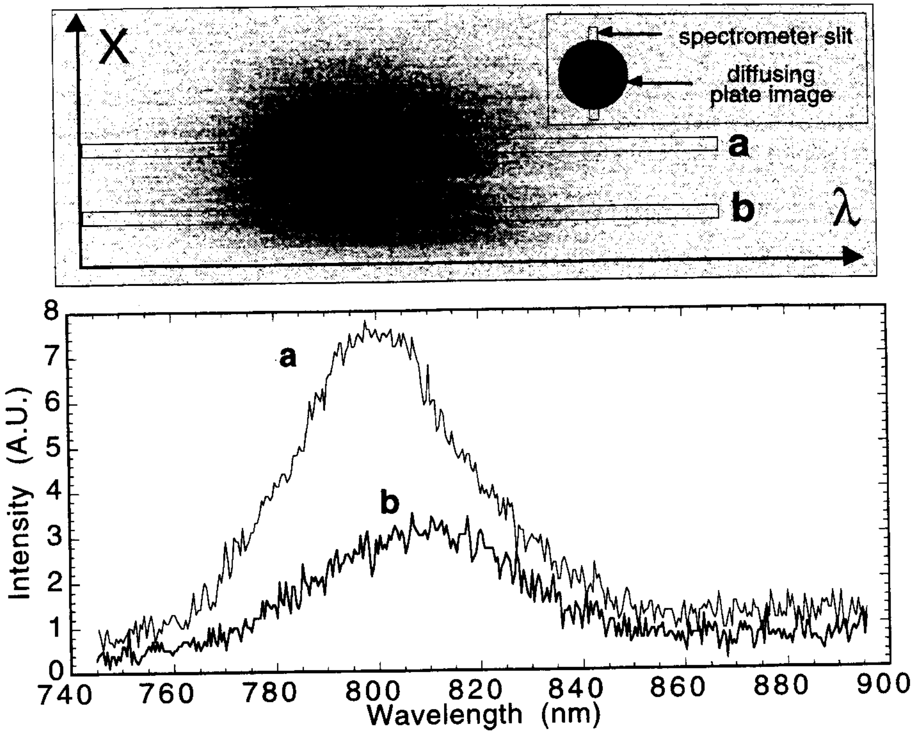

FIGURE 6. Lineouts of space resolved spectra (upper) of the pulse cross-section taken at the centre (a) and at the boundary (b) of the cross section. A blue-shift measured at the boundary of the cross-section (10Å) is approximately twice that measured at the centre of the pattern.

A comparison of lineouts of the space-resolved transmitted spectrum shows that the measured blue-shift decreases when outer portions of the transmitted pulse pattern on the diffusing screen are selected. In particular, the lineout 'b' shows basically no shift from the unperturbed laser spectrum. As discussed below, it is clear that strong variations of the laser-target coupling conditions take place across the focal spot in our interaction condition.

DISCUSSION

The whole set of data presented below, consistently shows a transition from a very low transmission regime to an almost full transparency of the dense laminar plasma, with increasing laser intensity on target. The transparency is observed at an intensity of 3×10^{18} W/cm^2, at which the value of the normalised relativistic momentum is $a_o \cong 1.2$. Therefore, relativistic changes to the electron mass are expected to be marginal, and we can reasonably neglect effects of self-induced transparency as that calculated in Ref.3 for $a >> 1$ and electron densities above n_c, but well below the solid density.

If we consider in turn the anomalous skin effect, the numerical simulations of Ref.8 provide data for the transparency of laminar solid density plasmas of 0.1 μm thickness. These results can be reasonably extrapolated to the conditions of a fully ionised plastic foil of 0.1 μm thickness, as in our experiment. The fraction of energy transmitted resulted from the simulation in the range of 10^{-5} to 10^{-6}, higher than in both cases of normal skin effect and Weibel theory, but still orders of magnitude lower than the transmittivity measured in our experiment at 3×10^{18} W/cm^2.

Further, to our knowledge, no theoretical models neither 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 could be enhanced by the extremely short duration of the laser pulse. In fact, at the lower and intermediate intensity the blue shift in the spectrum of the transmitted pulse is a clear signature of ultra-fast ionisation. This is well supported also by the amount of the blue shift, 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 ultra-fast decrease of the refractive index due to the laser induced ionisation, we have [10]

$$\delta\omega = -(L/c)(\Delta\mu/\Delta t)\omega_o \qquad (1)$$

Considering a change of the refractive index $\Delta\mu \approx -1$, as that due to a transition from zero electron density to the critical density, we can use Eq.1 to evaluate the time-scale Δt of such a transition. By taking the interaction path equal to the foil thickness $L = 0.1\mu m$, we find $\Delta t \approx 20$ fs and $\Delta t \approx 13$ fs for the low and intermediate intensity, respectively. These values are fully consistent with the rise time of the laser pulse thus supporting the assumption that ultra-fast ionisation occurs and providing indirect evidence that the plasma thickness is indeed comparable to the original foil thickness. The reduced shift measured at the boundaries of the transmitted pulse patter (Fig.6), where the laser intensity is lower, gives a larger Δt i.e. suggesting that a smaller ionisation rate can be inferred for those interaction regions. On the other hand, the spectrum taken in conditions close to the full transparency at 3×10^{18} W/cm^2 shows no substantial shift implying that in this case the ionisation process may involve only a small portion of the leading part of the pulse while the bulk of the pulse energy goes through the target undergoing no detectable changes.

It has been suggested that the laser pulse may propagate deeply in the overdense plasma by pushing electrons away from the interaction region due to ponderomotive forces. It may be interesting to note that longitudinal and transversal ponderomotive forces are expected to be of the same order for a 30 fs pulse focused in a 10 μm spot. This effect has been demonstrated[4] in numerical simulations with moderately overdense plasmas and at laser intensities higher that those of our experiment. In fact, production of ponderomotive-force electrons has been demonstrated experimentally in the interaction of short pulses with solid targets at relativistic intensities[5]. In that experiment the authors point out that when thin targets (slightly thicker than those used in our experiment) were used instead of massive target, *the number of MeV electrons detected along the laser propagation axis in the forward direction sharply increased (X30).* It is important to point out that preliminary measurements carried out in our experiment using NaI(Tl) detectors placed in the backward direction, showed that ≈MeV photons were generated, probably originating from bremsstrahlung emission from energetic electrons. All these observations on the production of energetic electrons and γ-ray photons suggest that mechanisms of acceleration of electrons are particularly effective in the interaction of intense short pulses with thin targets.

From the point of view of the transparency, however, due to the density of our plasma, electrons ejected from the focal spot are rapidly called back by background ions due to enormous electrostatic forces. Simple calculations show that, in our conditions, the restoring force of background ions prevents motion of the bulk of electrons beyond a negligible fraction of the focal spot diameter. Consequently, ponderomotive force cannot explain the observed transparency.

SUMMARY

We studied the interaction of intense 30fs laser pulses with 0.1μm plastic targets. The measured transmittivity for laser intensities greater than 10^{17} W/cm^2 is orders of magnitude higher than the transmittivity predicted by current models. In particular, when the intensity was 3×10^{18} W/cm^2, i.e. only weakly relativistic, we observed almost complete transparency of solid density laminar plasmas without substantial modification of the spectrum. At 3×10^{18} W/cm^2 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, ultra-short, aberrated laser pulses. Ionisation times as short as 10fs where inferred from space-resolved spectra of transmitted laser light. In our opinion, the observation of solid plasma transparency to ultra-short pulses at intensities corresponding to $a \cong 1.2$ 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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