PICOSECOND INTERFEROMETRY OF PLASMAS BEFORE AND AFTER SHORT LASER PULSE PROPAGATION

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The propagation of an intense short EM wave packet through a plasma is of great relevance for both basic physics and applications, the latter including new schemes of fuel ignition for Inertial Confinement Fusion (ICF)[1], X-ray lasers[2], plasma based electron accelerators[3]. Furthermore an unexplored class of light induced effects in hot ionised matter can be studied, since the oscillating electric field on the electrons can overcome the atomic field and the electron quiver velocity can approach relativistic values. At the same time, some phenomena playing a crucial role with long pulse interaction, as hydrodynamic motion and collisional absorption, can be virtually suppressed. The experimental study of the propagation of short, intense laser pulses through preformed, underdense plasmas is therefore of great physical interest; this study requires the use of diagnostics which allow for a detailed knowledge of the parameters of the preformed plasma and which are sensitive to the effects of short pulse propagation in the plasma.

In this communication we present novel experimental results on the propagation in an underdense plasma of short (700 fs) laser pulses at irradiances from 10^{16} Wcm^{-2} to 10^{17} Wcm^{-2}. Though below relativistic values, this range of irradiances has not been explored so far for propagation in long-scalelength plasmas of interest for ICF. We shall focus our attention mainly on the use of picosecond interferometry to characterise the preformed plasma and to study the effect of short pulse propagation. The use of short (<1 ps) laser pulses for interferometry has lead to a very significant improvement in the 2-D density

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mapping of the plasma. Beside interferometry, other diagnostics included calorimetry and cross-section imaging of the interaction pulse transmitted through the preformed plasma.

The experiment was performed at the Central Laser Facility of the Rutherford Appleton Laboratory (UK). The set-up geometry is essentially the same that was used in a previous experiment on long (600 ps) pulse interaction[4]. The plasma was produced by four 600 ps, 1.053 μm laser "heating" beams focused on target in opposite pairs. The target consisted of Al disks coated on very thin (0.1 μm) plastic stripes. The disk thickness was 0.4 μm and the diameter was 0.8 mm, matching the size of the laser spot. The irradiance on each side of the target was varied in the range between 10^{13} Wcm^{-2} and 10^{14} Wcm^{-2}. A 700 fs laser pulse, obtained with the Chirped-Pulse-Amplification (CPA) technique, was interacted with the preformed plasma by 2 ns after the peak of the 600 ps laser beams. The short interaction pulse beam was focused with a large *f*-number along the plasma main axis in a spot much smaller than the plasma cross section, in order to avoid boundary refraction effects. A minor portion of the short pulse energy was split, frequency doubled, and used as an optical probe for interferometry.

The interferometry used a modified Nomarski configuration[5]. In this interferometer, a Wollaston prism is used to produce two separate ortogonally polarised images of the plasma surrounded by an unperturbed background. Interference between each of the two images and the background of the other image is achieved by putting a polariser before the film plane, oriented at 45° with respect to the polarisation axis. A spatial filter was inserted before the Wollaston prism in order to reduce noise from plasma self-emission and probe scattered light. The line of view of the interferometer, "*y*", was perpendicular to the interaction beam axis, "*x*".

Two-dimensional density profiles of the plasma were obtained from the analysis of the fringe pattern in the interferometer image plane. If the plasma has cylindrical symmetry, the phase shift induced by the plasma in the (*x*,*z*) plane, perpendicular to the interferometer axis, can be written in terms of the electron density $n_e(r,x)$ as

$$\Delta\phi(x,z) = \frac{2\pi}{\lambda n_c}\int_z^{r_0} \frac{n_e(r,x)}{\sqrt{r^2-z^2}}\, r dr \tag{1}$$

where *r* is the radial coordinate from the interaction axis, r_o is the plasma radius, λ is the probe beam wavelength, n_c is the critical density corresponding to λ. A detailed discussion of Eq.1 and its underlying approximations can be found elsewhere.[4] The fringe intensity $I(x,z)$ in the interferometer image plane can be written generally as[6]

$$I(x,z) = a\,(x,z) + [c(x,z)\exp 2\pi\, i f_u x + c.c] \tag{2}$$

where $c(x,z) = 1/2b(x,z)\exp(i\Delta\phi(x,z))$, f_u is the number of fringes per unit length, and $a(x,z)$ and $b(x,z)$ account for background nonuniformities and fringe visibility. In Eq.2 $c(x,z)$ contains the physical information on plasma density; the background contribution can be separated taking the Fourier transform of Eq.1:

$$F_I(f,z) = F_a(f,z) + F_c(f-f_u,z) + F_{c*}(f+f_u,z) \tag{3}$$

If the scalelength of background uniformities along *x* is much larger than the fringe separation, the background contribution in Eq.2 can be separated in order to obtain $F_c(x,z)$; $c(x,z)$ is then obtained via inverse Fourier transform; in practice this is carried out using a

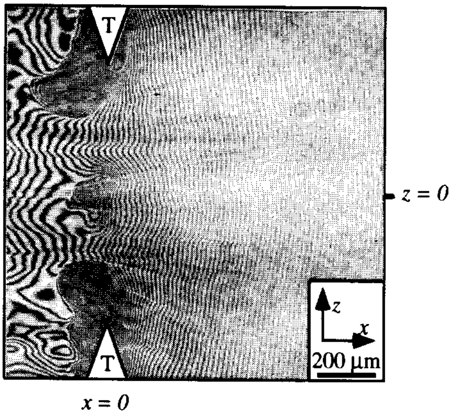

Figure 1. Interferogram of the preformed plasma taken 2.2 ns after the peak of the heating laser pulses, for an intensity of 5.0×10^{13} Wcm^{-2} on target.

Fast Fourier Transform code. Finally $\phi(x,z)$ is deduced from the logarithm of $c(x,z)$ and the 2-D density map $n_e(r,x)$ is obtained by Abel inversion of Eq.1. It must be noted that also small-scale perturbations of the electron density can contribute to the phase shift. The interferometer was found to be very sensitive to these density perturbations[4], making this interferometric technique very effective in detecting density inhomogeneities in the preformed plasma or perturbations induced by the interaction pulse.

A representative interferogram of the preformed plasma before short pulse interaction is shown in Fig.1. The intensity of the heating beams on each side of the Al target was 5.0×10^{13} Wcm^{-2}. The probe pulse was delayed by 2.2 ns with respect to the peak of the heating beams. The 2-D density map reconstructed from the fringe pattern in Fig.1 is shown in Fig.2.

It is very interesting to compare the interferogram in Fig.1 with the interferograms previously obtained with a very similar interferometer configuration, but using a "long" 100 ps probe pulse[4]. In those interferograms the fringe visibility vanished in the denser region of the plasma and thus it was not possible to measure the electron density in that plasma region. This effect was due to the electron density evolution which smeared out part of the pattern during the probe pulse. In fact, the density variation rate in the denser region was high enough to induce, in 100 ps, a phase change that leads to an almost complete loss of visibility. Reducing the probe duration to less than 1 ps eliminates the "smearing" effect completely, making fringes visible over the whole interferogram and thus allowing for a complete density mapping of the plasma.

The detailed density mapping of the preformed plasma at times corresponding to the interaction with the short pulse was very important in the study of the short pulse propagation. We found that the propagation is independent from the short pulse irradiance in the considered range, but strongly depends on the plasma density distribution. Fig.3 shows the fraction of the short pulse energy transmitted through the preformed plasma versus the heating beams irradiance I_H on the Al target; it is evident that short pulse transmission strongly increases over a "threshold" value of I_H. These data were compared with density maps for different values of I_H, which showed that at $I_H \approx 7\times10^{13}$ Wcm^{-2} the density along the plasma symmetry axis at 2 ns after plasma formation turns from a maximum to a local minimum. This effect is purely hydrodynamic and is in good agreement with 2-D simula-

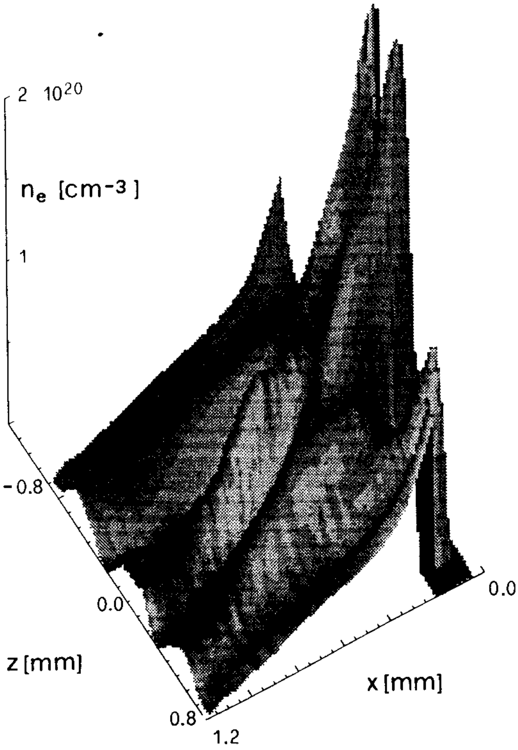

Figure 2. 2-D electron density map reconstructed from the interferogram shown in fig.1.

tions performed with the POLLUX code[7]. In this way a sort of channel is produced, allowing for a good propagation of the short pulse. Correspondingly, cross-beam images showed that in presence of the density minimum the short pulse beam avoids strong refraction from the plasma.

A number of interferograms were also taken after propagation of the short pulse through the preformed plasma. The high sensitivity of the interferometer allowed evidenti-

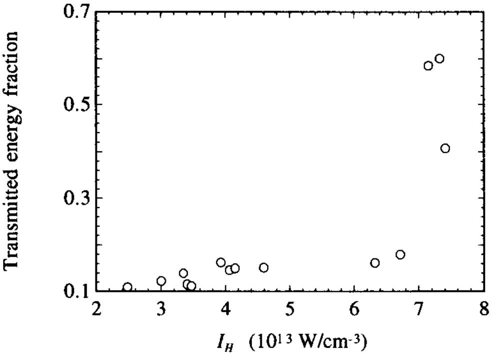

Figure 3. Fraction of the incident short pulse energy collected forward vs. heating beams irradiance I_H on each target side.

ate density perturbations of the order of 1/10 of the local electron density along the interaction axis, probably produced by ionisation. These data are presently under investigation.

In conclusion, our experimental results suggest that a short pulse of subrelativistic intensity is likely to propagate through an underdense plasma with very low losses provided a (even weak) density minimum is set along its axis. On the contrary, it was previously found that propagation of longer (600 ps) pulses through the preformed plasma was heavily absorbed, scattered and affected by self-focusing[8]. The use of picosecond interferometry was found to be very effective to characterise the preformed plasma, thus shedding light on the physics of short pulse propagation.

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