PREFORMED PLASMA STUDIES WITH CPA VULCAN PULSES:

I. Progress in Plasma Characterisation for Interaction Studies

II. Propagation of Ultra-Short Pulses through Underdense Plasmas

An experiment performed with funding from the
HCM Large Facilities Access Programme

Access to the High Power Laser Facilities
at the Rutherford Appleton Laboratory

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SUMMARY

This report describes the experiment carried out at the CLF from the 17th April to the 29th May 1995. The experiment, funded by the Framework III Large Facilities Access Scheme, was proposed as 'The propagation of picosecond pulses through preformed plasmas', led by Dr Antonio Giulietti, Istituto di Fisica Atomica e Molecolare, Pisa, Italy, and carried out by a visiting team of young researchers from Italy and assisted by scientists from Imperial College, London. The results obtained covered a much larger field than the original experimental proposal and hence this report has been split into two distinct parts.

Experimental Results

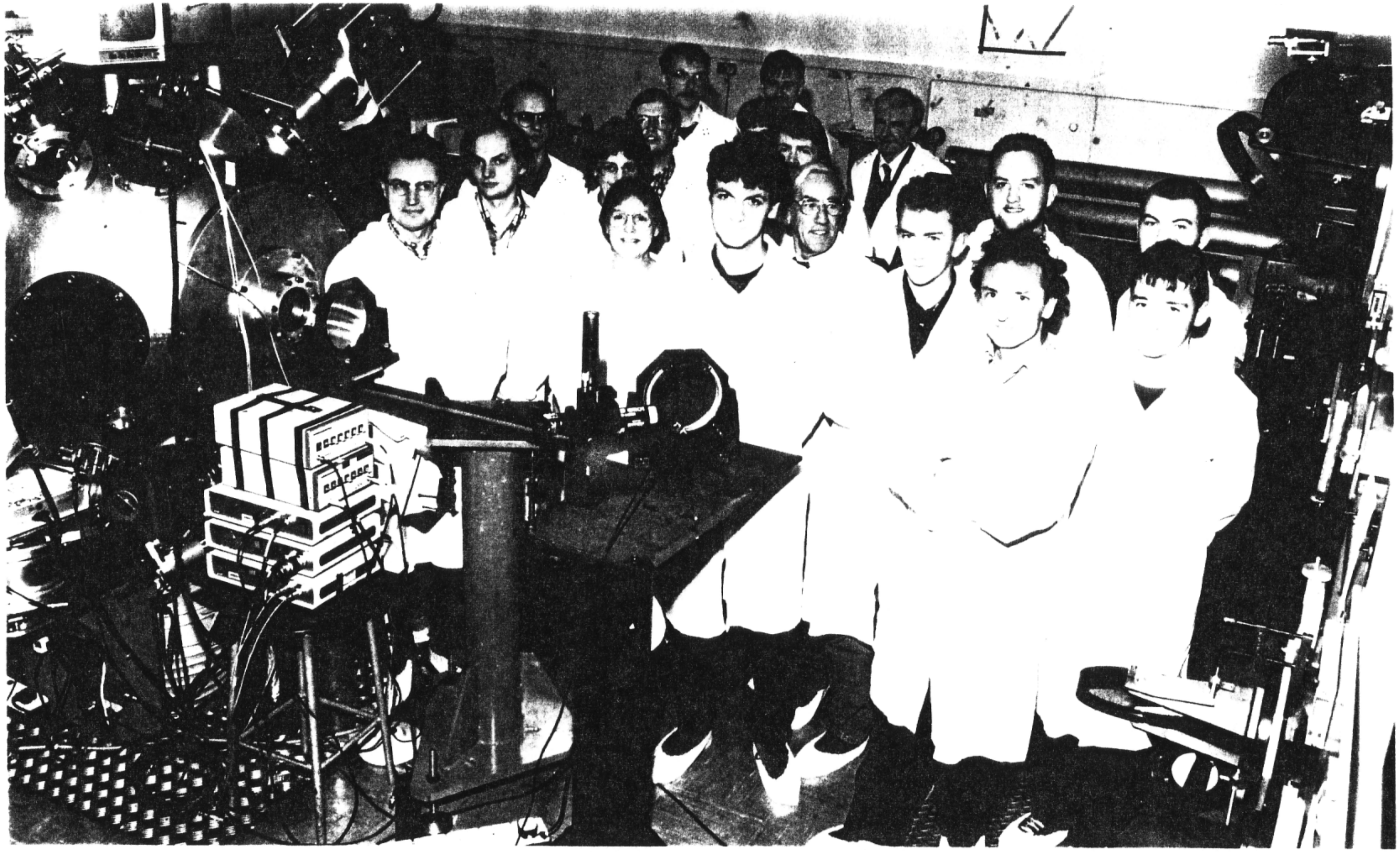
I. Progress in Plasma Characterisation for Interaction Studies

- Proved the technique of ps temporal resolution optical interferometry
- Tested different target designs
- Demonstrated improved plasma density characterisation
- Successfully compared the results to a 2-D computer hydrocode

II. Propagation of Ultra-Short Pulses through Underdense Plasmas

- Studied the propagation of a sub ps pulse through a preformed plasma - relevant to ICF Fast Ignitor Scheme
- The propagation is not affected by the short pulse irradiance in the range 10^{16} to 10^{17} W/cm^2
- The propagation is critically affected by the density distribution of the preformed plasma
- The fractional transmitted energy showed a threshold depending on the heating beam irradiance
- Modifications to the plasma density profile induced by the interaction pulse were measured via optical interferometry

The CLF makes beam time at its facilities available to European Researchers with funding from DG-XII, CEC under the Large Facilities Access Scheme. For further information contact Dr. Chris Edwards at the CLF. Tel: (0)1235 445582, e-mail: c.b.edwards@rl.ac.uk



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Refereed Publications

M.Borghesi, A.Giulietti, D.Giulietti, L.A.Gizzi, A.Macchi and O.Willi. "Characterisation of Laser Plasmas for Interaction Studies: Progress in Time-Resolved Density Mapping." Accepted by **Phys Rev** E

M Borghesi, A Giulietti, D Giulietti, L Gizzi, A Macchi, D Neely and O Willi. "Underdense Plasmas from Thin Foils: Production, Characterisation and Short-pulse Interaction." Submitted for publication.

Conference Presentations

24th ECLIM, Madrid, Spain, June 3-7, 1996.

M Borghesi, A Giulietti, D Giulietti, L Gizzi, A Macchi, D Neely and O Willi. "Underdense Plasmas from Thin Foils: Production, Characterisation and Short-pulse Interaction."

IX International Symposium on "Ultrafast Processes in Spectroscopy", Trieste, Italy, October 30 - Nov 3, 1995.

A Giulietti, M Borghesi, C Danson, D Giulietti, LA Gizzi, A Macchi and D Neely. "Picosecond Interferometry of Plasmas Before and After Short Laser Pulse Propagation."

2nd European Workshop on the Generation and Application of ultra-short X-ray pulses. Pisa, Italy. 20-23 Sept. 1995

A Giullietti. "Propagation of Short Laser Pulses Through Underdense Plasmas."

Internal Reports

A.Giulietti, M.Borghesi, C.Danson, D.Giulietti, L.A.Gizzi, A.Macchi and D.Neely. "Short Pulse Propagation Through Preformed Plasmas." Central Laser Facility Annual Report 1995-6, RAL Report TR-96-066, p 22-24.

M.Borghesi, A.Giulietti, D.Giulietti, L.A.Gizzi, A.Macchi and O.Willi. "Production and Characterisation of Underdense Plasmas for Interaction Studies." Central Laser Facility Annual Report 1995-6, RAL Report TR-96-066, p 25-27.

I. PROGRESS IN PLASMA CHARACTERISATION FOR INTERACTION STUDIES

Introduction

Time-resolved probe interferometry was used to obtain complete density mapping of laser produced plasmas. The plasma was produced by symmetrical irradiation of thin targets, to be used for short pulse delayed interaction experiments. The progress in the plasma characterisation due to the use of a picosecond pulse probe is reported, and the relative merits of different target designs are also discussed. The 2-D density maps obtained appear to be in substantial agreement with 2-D hydrocode predictions.

Laser heating of thin targets is nowadays recognised as an established method (also known as the exploding foil technique) for the production of laboratory plasmas [1]. With this technique, plasmas within a wide range of densities and temperatures can be obtained by appropriately choosing the heating beam parameters. Analytical models [2] have been developed in order to predict the hydrodynamic expansion of such plasmas. Numerical codes presently in use can provide simulations of the plasma temporal evolution from both an hydrodynamic and an atomic physics viewpoint [3].

Though plasmas produced from exploding foils were originally considered for x-ray laser studies [4] experiments studying the interaction of suitably delayed laser pulses with preformed plasmas proved to be important for Inertial Confinement Fusion (ICF) studies [5]. Several methods of plasma production from thin targets have therefore been developed for this specific purpose, together with diagnostic methods able to describe as best as possible the preformed plasma conditions.

Amongst the diagnostics for plasma characterisation, optical interferometry is a well known and widely used technique for electron density measurements. Interferometry with delayed probe pulses has been also widely used to detect the effect of the delayed interaction. Recent works [6,7] report the use of interferometric methods with temporal resolution of tens of picoseconds to study the propagation of intense laser pulses through preformed plasmas. In this respect, the success of novel applications, such fast ignitor scheme for ICF [8] and particle acceleration by plasma waves [9], relies on the understanding of physical phenomena that take place on picosecond and subpicosecond time scales. In order to resolve the interaction processes on these timescales, the use of probe pulses of comparable duration appears to be necessary. Shadowgraphy and interferometry with resolution of a few picoseconds have already been successfully used in the past to study the temporal evolution of laser produced plasmas [10]. The recent enormous advances in laser technology, and in particular the development of the Chirped Pulse Amplification (CPA) technique [11], gave a new impulse to these diagnostics. The high power and coherence of the short pulses produced with this technique consent to probe large regions of plasma. Furthermore, since in short pulse interaction studies the probe is normally split off from the interaction beam, synchronisation of probe and interaction pulse within a few pulse lengths can easily be obtained by optical delay.

In a previous work [12], we already produced and characterised plasmas for interaction studies, obtained from thin foils exploded by symmetrical irradiation. In that study, the density mapping of the denser, inner region of the plasma was restricted by both probe duration (100 ps) and target configuration. In this paper we present results showing progress toward a complete and reliable density mapping of the plasma, determined by the use of a shorter probe pulse and two different and complementary target configurations. In the following the main features of the previous experiment will be shortly discussed, in order to allow a comparative discussion of the density maps obtained in the previous and in the current measurements.

In the previous experiment, the plasma was produced by uniform laser irradiation from opposite sides of Al disks (400 μm in diameter) coated on thin, narrow plastic stripes (as wide as the Al dot). Time-resolved X-ray spectroscopy was used to infer the electron temperature from line intensity ratios between H-like and He-like lines, while 2-D electron density maps were obtained using an interferometric technique. The 100 ps temporal resolution of the interferometry (i.e. the duration of the laser pulse used as an optical probe) resulted in limiting the readability of the interferograms. In fact, the visibility of the fringes dropped to zero in the inner region of the plasma. Here the density variation during 100 ps was large enough to smear out the fringe pattern. A complete density map of the plasma could be obtained only at late stages of the plasma evolution (typically after 4 ns from the peak of the heating pulse), when the density variation rate had become considerably lower. At these times, however, the plasma was rather cold, and could not be characterised completely, since temperature measurements via K-shell line spectroscopy were not possible. Another problem encountered was the deviation of the plasma from cylindrical symmetry, in consequence of the target design. This aspect was also discussed in ref.[12]. Since the spot of the heating beam was larger than the Al dot, a plasma was produced from the plastic substrate, mostly above and below the dot, and this resulted in confining the Al plasma in the vertical direction. Consequently, the symmetry of the Al plasma was ellipsoidal rather than cylindrical, with the longer axis along the probe line. Since Abel inversion techniques (through which the electron density map is obtained from the interferogram) are based on the assumption of cylindrical symmetry of the plasma, a systematic overestimation was introduced to the density measurements. The deviation from cylindrical symmetry was considerable close to the original foil target position, and resulted in an overestimate of up to 40% in the peak plasma density, when compared with hydrodynamic simulations [12].

Since the plasma was produced with the aim of studying the propagation of a short laser pulse (see part II, Propagation of Ultra-Short Pulses through Underdense Plasmas) from the RAL CPA laser, the use of a short pulse optical probe appeared to be desirable for two reasons: a) for measuring the electron density distribution in the central denser region of the plasma at times of interest; b) to probe the region perturbed by the short interaction pulse with sufficient temporal resolution. For this reason, a fraction of the 1 ps CPA beam energy was used in a probe beam for interferometry. At the same time a novel thin target configuration was employed in order to minimise perturbation of the cylindrical symmetry.

Experimental Set-up

The plasma was produced by four 600 ps, 1.053 μm heating beams of the Vulcan laser, using the configuration reported in ref.[12]. The heating beams were superimposed on target in two opposite pairs in a 650-μm focal spot for an irradiance on each side below 10^{14} W/cm^2. Each pair was composed of two beams at angle of +13 and -13 degrees to the target normal, respectively. The targets used were Al disks, alternatively coated onto 0.1 μm thick, plastic foil support (considerably wider than in the previous experiment), or held by four tiny Al arms in the shape of a X. This second type of targets was obtained by etching of an Al thin deposit on a plastic foil. The diameter of the dots was 800 μm and their thickness 0.4 μm. The two target shapes are schematically drawn together with the corresponding interferogram in the figures shown in the next section. The 1 ps CPA beam, frequency doubled to 0.53 μm, was used as an optical probe for interferometric measurements in a line of view parallel to the target plane. The plasma was probed with different delays, typically around 2 ns after the peak of pulse. At these times the size of the plasma was 1~2 millimetres. A modified Nomarski interferometer [13] was employed to detect the phase changes undergone by the probe beam and measure the electron density profiles. The probe line set-up was different from the configuration of the previous experiment. A confocal optical system (composed of a microscope objective and a f/10 lens) imaged the plasma and recollimated the probe beam. A third lens was used in order to relay the image plane, so that spatial filtering could be performed in the Fourier plane of this lens in order to reduce plasma emission noise. The Wollaston prism was located close to this plane.

Density Mapping

As stated before, when the plasma was characterised via interferometry with 100 ps resolution, the density was not measurable in the inner regions of the plasma, even at times at which the peak density was well below critical. In fig.1 an interferogram taken 3 ns after the peak of the

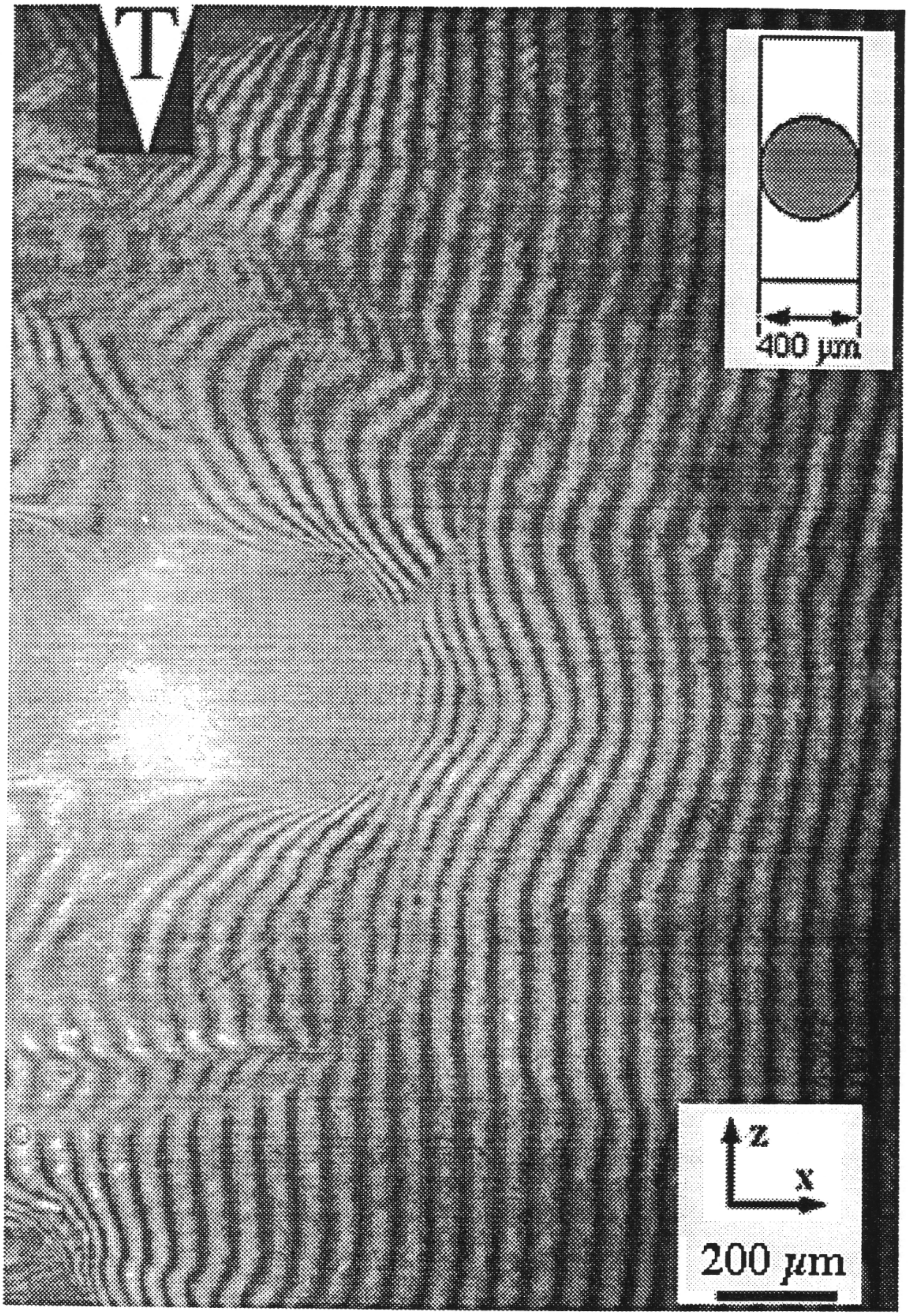

Fig.1 Interferogram taken 3 ns after the peak of the heating pulses using a 100 ps probe pulse. The target was a Al disk (400 µm diameter) on a narrow plastic stripe. The heating irradiance was 5 10^{13} W/cm^2 on each side of the target. The original target position is shown by a T-wedge.

heating pulse with the 100 ps probe pulse is shown. It can be noticed that over a wide region (extending longitudinally to about 300 μm from the original target position) the visibility of the fringes is zero. The loss in fringe visibility was caused by density variations taking place throughout the duration of the probe pulse. The use of a considerably shorter probe pulse was extremely effective in overcoming this limitation. Using the picosecond probe, we were able to measure the density profile almost over the length of the whole plasma as early as 2 ns after the peak of the heating pulses. The interferogram shown in fig. 2 was in fact obtained 2 ns after the peak of the heating pulses. The plasma was preformed from an Al disk coated on a large plastic foil, with an heating irradiance comparable to the case of fig.1. The improvement in the interferometric characterisation of the plasma due to the shorter probe pulse duration is clearly evident from comparison with the interferogram shown in fig.1, obtained with a 100 ps probe pulse. It can be seen that in that case, even at a later time and in the presence of a smaller plasma, the visibility of the fringes was lost over a considerably wider region.

However, even with the picosecond probe, when using Al disks on large plastic foils as targets, a small region of the interferogram is still obscured by the shadow of the dense, slowly expanding plasma created on the outer edges of the foil by the tails of the laser spot. In the interferogram shown, this shadow extends to 150 μm from the centre of the target. On the other hand this kind of target ensures a high degree of cylindrical symmetry of the plasma. Plasma is produced from the plastic substrate all around the Al plasma, confining it symmetrically.

The method used to obtain the density map from the interferogram was the same as used in the previous measurements, involving a Fourier transform method [14] for the phase extraction, and subsequent Abel inversion of the phase distribution. A detailed discussion of the sensitivity of this technique can also be found in [12]. The algorithm proposed by Barr [15] was used this time to invert the Abel integral. The phase distribution and the 2-D density map obtained from the interferogram of fig. 2a are shown in fig. 2b and 2c.

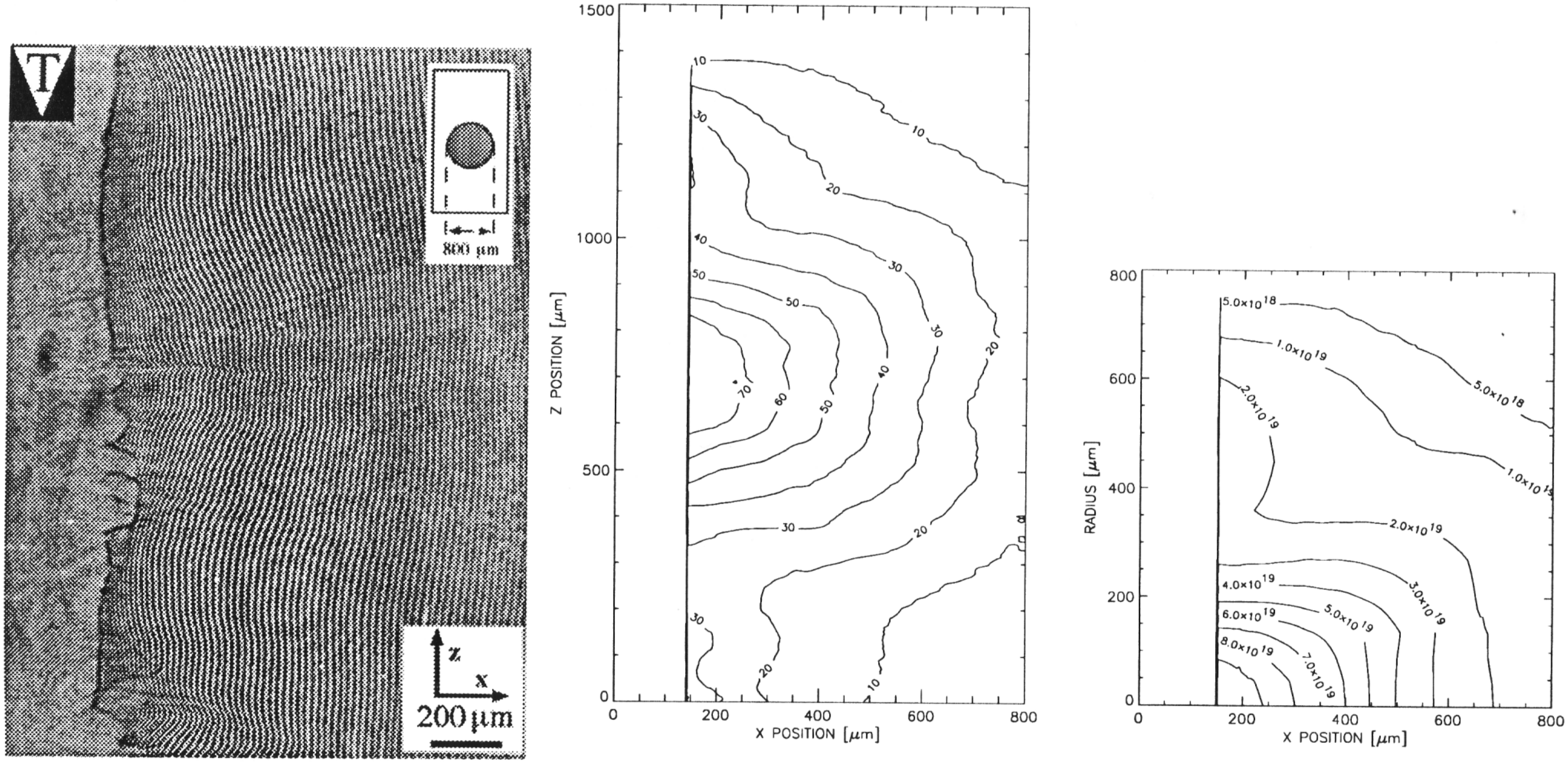

Fig.2 (a) Interferogram taken 2 ns after the peak of the heating pulses using a 1 ps probe pulse. The target was an Al disk (800 μm diameter) on a large plastic foil. The heating irradiance was 7 10^{13} W/cm^2 on each side of the target. (b) Phase map obtained from the interferogram using a Fourier transform method. The phase is expressed in radians.(c) Density map obtained by Abel inversion of the phase map. The density is expressed in el/cm^3. The X position is measured with respect to the original target position, the Z position and the radius with respect to the symmetry axis.

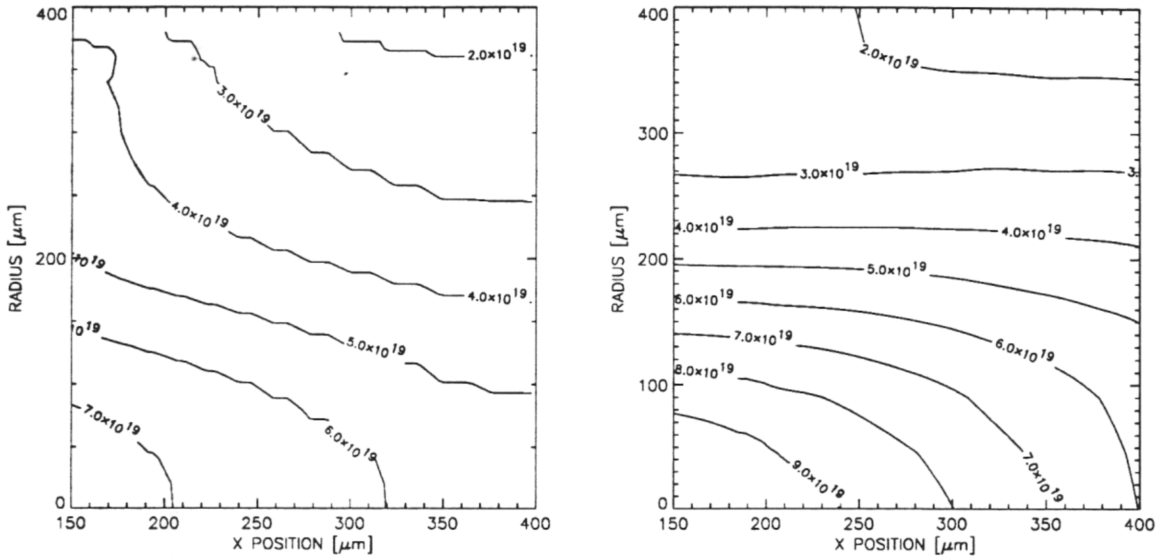

Fig.3 (a) 2-D simulation for the density profile in the experimental condition of the interferogram of fig. 2. (b) Experimental profile for comparison

The hydrodynamic expansion of the plasma was simulated using the 2D Eulerian hydro-code Pollux [16]. The code models laser absorption via inverse Bremsstrahlung and thermal transport via flux-limited Spitzer-Harm conductivity. Ionisation is calculated assuming Local Thermodynamic Equilibrium (LTE), while a perfect gas equation of state is used for electrons. A single side irradiation configuration was employed; the target thickness assumed in the simulations was half the experimental value. In order to simulate the laser irradiation from both sides of the target, reflective boundary conditions for the laser energy flux were imposed at the boundary of the simulation box opposed to the laser.

In fig. 3 the code prediction for the density profile in the same conditions of the interferogram of fig. 2 is shown. The agreement with the experimental data is quite good, confirming that the assumption of cylindrical symmetry is justified for plasmas produced with the new target configuration. The residual, though insubstantial, discrepancy may be attributed to the fact that the plasma produced from the plastic substrate around the Al dot can confine the Al plasma. Thus the density in the central plasma region may result higher than in the case of completely free expansion, as modelled by the code. However, the substantial agreement between experiment and simulation gives confidence in 2D hydrocodes as a reliable and useful tool in designing experiments in this configuration.

Targets in which the Al disk is held by four Al arms (*X-shaped* targets) were also used. The main advantage introduced by the absence of the plastic substrate was that the field of view of the probe beam was not limited by any shadow, but extended virtually throughout the whole length of the plasma. An interferogram of a plasma produced from a *X-shaped* target is shown in fig.4. Unfortunately the width of the Al arms could not be reduced below 200 micron, due to difficulties in the target preparation. Consequently, the plasma produced on the Al arms by the wings of the laser spot introduced a substantial perturbation to the symmetry of the whole plasma. This resulted in a lower accuracy in the interferometric determination of the absolute electron density than using the other type of target. However plasmas produced from these targets appear to be particularly suitable for interaction studies, as density variations induced in the plasma by an interaction pulse can be observed and evaluated even in the inner part of the plasma.

Finally, we recall that the interferometric technique described above is quite effective in detecting small-scale variations of the plasma density. The substantial absence of small-scale inhomogeneity which results from the interferometric analysis makes this type of laser-produced plasma very useful as a test bed for delayed interaction experiments. Here we only notice that these conclusions can now be extended almost over the whole plasma extent, thanks to the progress in the plasma characterisation outlined in the present paper.

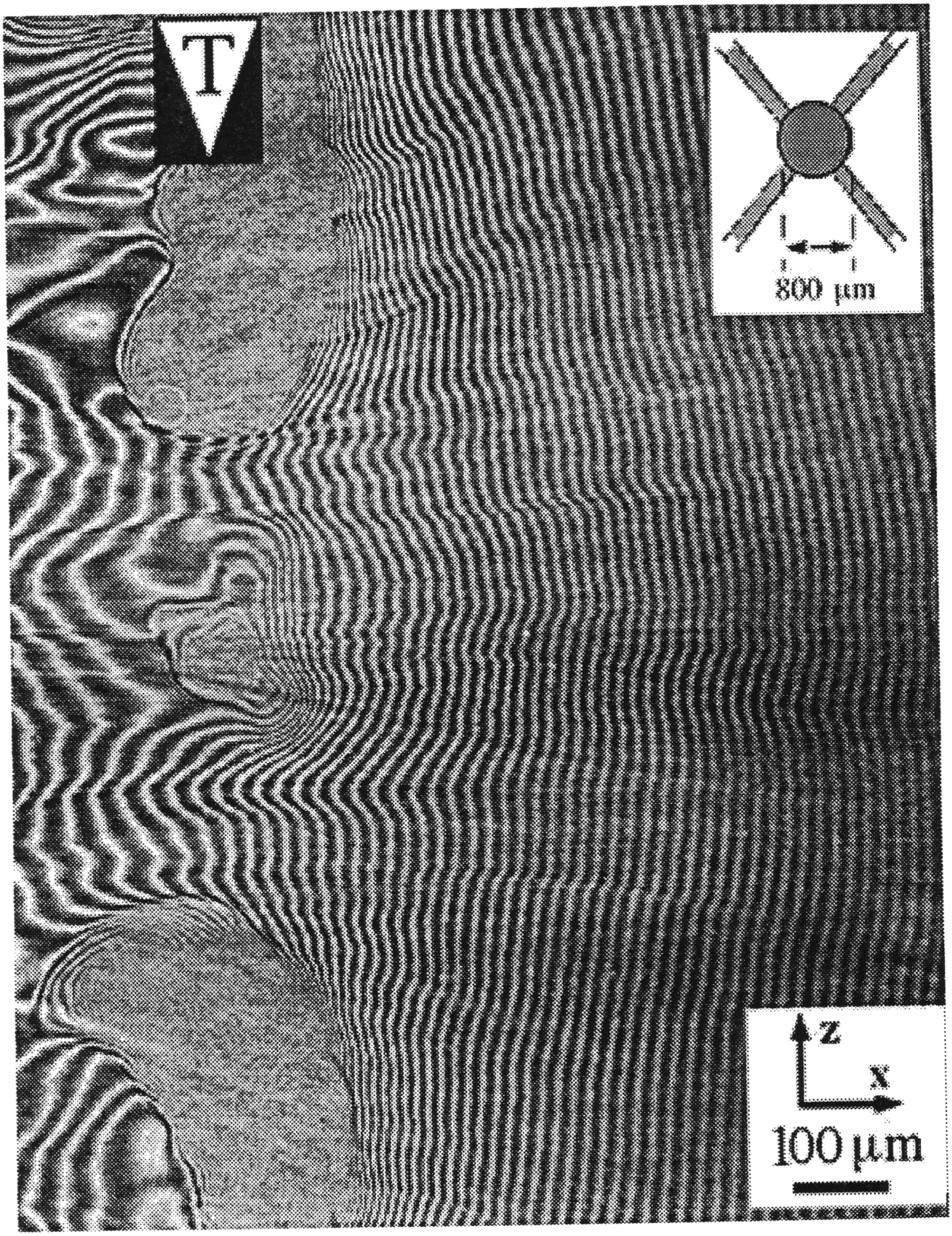

Fig. 4 Interferogram of a plasma produced from a *X-shaped* target, taken 2.2 ns after the peak of the heating pulses using a 1 ps probe pulse. The heating irradiance was $5\ 10^{13}$ W/cm^2 on each side of the target.

II. ULTRA-SHORT PULSE PROPAGATION THROUGH UNDERDENSE PLASMAS

Introduction

The study of the interaction of intense laser pulses with long scalelength plasmas is of crucial importance for laser-driven Inertial Confinement Fusion (ICF). In fact, the conditions of laser-plasma coupling in the expanding underdense *corona* surrounding the ICF capsule are critical in order to determine, for example, the level of energy absorption, the uniformity of energy deposition and the possible generation of fast electrons leading to undesirable target preheating.

Thanks to the recent developments in laser technology, the generation of ultrashort (<1 ps), high-intensity ($>10^{17}$ Wcm^{-2}) laser pulses is nowadays possible. In this regime the oscillating electric field can be comparable with the atomic field, and the electron *quiver* velocity can approach relativistic values; the ponderomotive pressure can be on the order of Gbars. On the other hand the laser pulse duration becomes comparable to the time scale of atomic and plasma processes. The study of laser-plasma interactions in this regime is of great physical interest since the dynamics is typically nonlinear and can lead to a number of new light-induced phenomena [17]. Moreover the propagation of an ultrashort pulse is of crucial interest for a number of scientific applications including the new *fast ignitor* scheme for ICF [8], which is presently being investigated in a number of experiments world-wide.

Our experiment was devoted to the study of the propagation of a short laser pulse with an intensity between 10^{16} and 10^{17} W cm^{-2} through a long-scalelength underdense ($n_e<n_c/10$), hot ($T_e>500$ eV) plasma, preformed by irradiation of a thin dot target by opposite pairs of laser beams as described in part I (Progress in Plasma Characterisation for Interaction Studies).

In the conditions of the experiment, collisional absorption of laser light was virtually suppressed due to the high intensity of the laser pulse. However, the short pulse energy could be absorbed through residual ionisation processes in the Al plasma. In this report we show and briefly discuss preliminary experimental results concerning the propagation of the short pulse in the plasma.

Set-up

The experiment was performed in the Target Area East of the Central Laser Facility. The target configurations used and the plasma production technique used were the same that have been discussed in part I.

The short interaction pulse (1 ps duration and energy up to 10 J) was generated with the CPA technique. A minor portion of the pulse was split, frequency doubled and used as an optical probe for interferometric measurements of the plasma density. The interaction pulse was focused with either a *f*/15 or a *f*/7.5 optics in a spot smaller than the plasma cross section, in order to avoid refraction effects at the plasma boundary. The short pulse interacted with the preformed plasmas 2-2.5 ns after the peak of the heating beams.

The propagation of the ultrashort pulse through the plasma was investigated via calorimetry and beam cross-section imaging of the fraction of the pulse transmitted through the plasma. Density perturbations induced in the plasma by the short pulse were studied by delaying the interferometric probe pulse in order to obtain density maps of the plasma at various instants after the interaction.

Study of Short Pulse Transmission

The energy of the short interaction pulse transmitted through the preformed plasma was monitored using a calorimeter. The background contribution due to plasma self-emission and scattered heating radiation was measured in shots in which only the heating beams were focused on target.

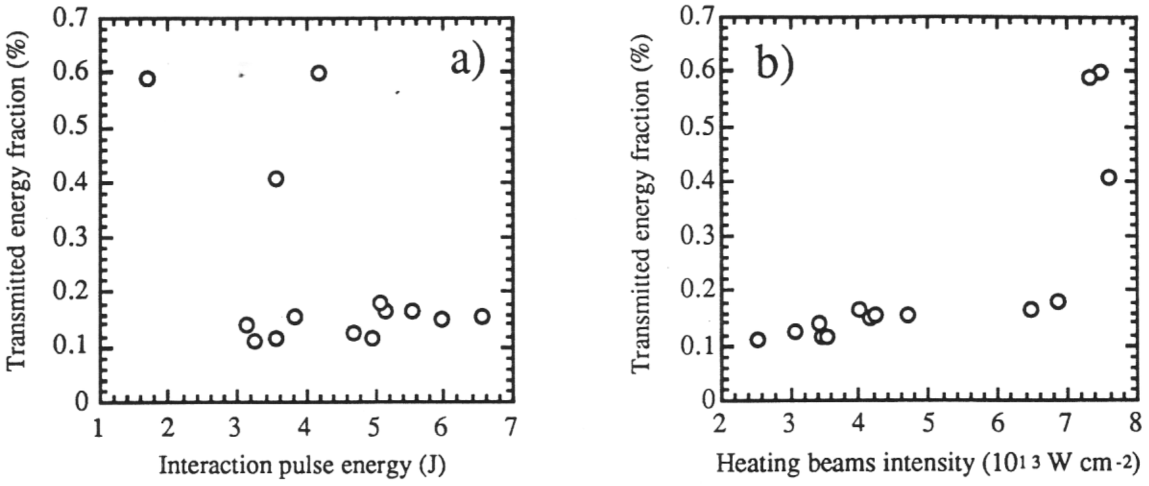

Fig. 5: transmitted energy fraction of the short interaction pulse vs. a) interaction pulse energy and b) heating beams energy.

The transmitted energy fraction of the short interaction pulse was studied as a function of both interaction and heating intensity. The results are shown in fig. 5. It can be noticed that in the investigated intensity range the short pulse transmission through the plasma is substantially not related to the energy of the short pulse itself, while it depends from the heating intensity through a sort of threshold mechanism. In other words, the hydrodynamic evolution of the preformed plasma appears to play an essential role in determining the conditions of the propagation process.

For heating intensities above $7\bullet10^{13}$ Wcm$^{-2,}$ the density and temperature distribution of the plasma 2 ns after the plasma production seems to be favourable for efficient propagation of the interaction pulse. 2-D hydrodynamic simulations performed using the POLLUX code [17] predicted, for an heating intensity of $8\bullet10^{13}$ Wcm^{-2}, the onset of a density depression along the symmetry axis approximately 2 ns after the plasma production (see fig. 6). This suggests that the short pulse propagates with low losses provided a (even weak) density minimum is set along the propagation axis. The influence of the preformed plasma conditions on the short pulse propagation can also be inferred from the cross-section images of the transmitted interaction beam. Fig. 7a shows the beam cross-section before the interaction chamber. The rectangular

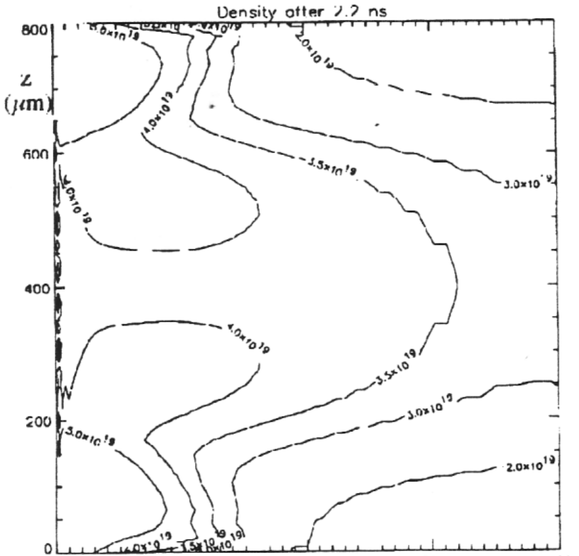

Fig. 6: POLLUX 2-D simulation of the plasma electron density at times corresponding to the short pulse interaction. The original target position is at x=0, y=400. The heating intensity is 8•10^{13} Wcm^{-2}.

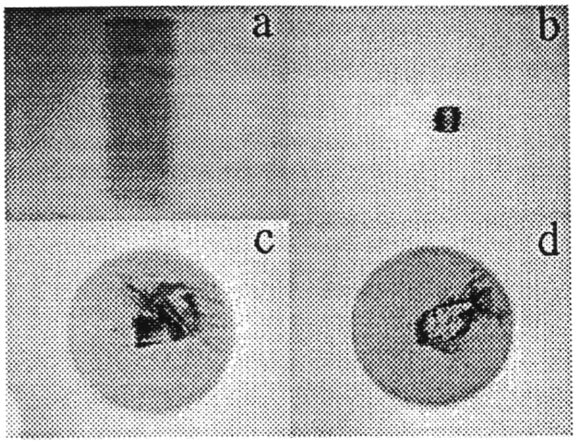

Fig. 7: cross-section images of the short pulse interaction beam a) before interaction: b) after propagation in absence of the plasma; c, d) after propagation in the plasma for two different values of the heating beams intensity (see text).

shape is due to the cut-off from the CPA gratings. Fig. 7b shows the beam intensity profile after propagation in the chamber in absence of the target. Finally, Fig. 7c and 7d show the beam cross section images after propagation through the preformed plasmas at heating irradiances of 5•10^{13} Wcm^{-2} and 8•10^{13} Wcm^{-2} respectively.

The background light is due to plasma self-emission and scattered light from the heating beams. From the comparison of the two latter images we see that, when the heating irradiance was higher, the short pulse was sensibly less refracted by the plasma.

Density Mapping After Short Pulse Propagation

As mentioned above, 2-D density maps of the preformed plasma before the interaction with the short pulse were reconstructed from the fringe intensity pattern of the interferograms. Due to the high interferometer sensitivity [12] even weak, small-scale density perturbations, as those induced by the short pulse propagation through the plasma, could be detected from the fringe displacement.

Fig.8 shows an interferogram taken 300 ps after the interaction of the CPA pulse with the plasma. From this interferogram a density perturbation of about 1/10 of the local electron density was evidenced along the short pulse propagation axis. This density perturbation was likely due to ionisation induced by the short pulse.

Since the light collected by the detector was spectrally filtered around 0.527 μm, the picture in fig. 8 is also an image in 2nd harmonic light (time-integrated) of the plasma. The dark features are due to 2nd harmonic produced both by the heating and the interaction pulses, and their analysis is also expected to give interesting information on the physics of the interaction.

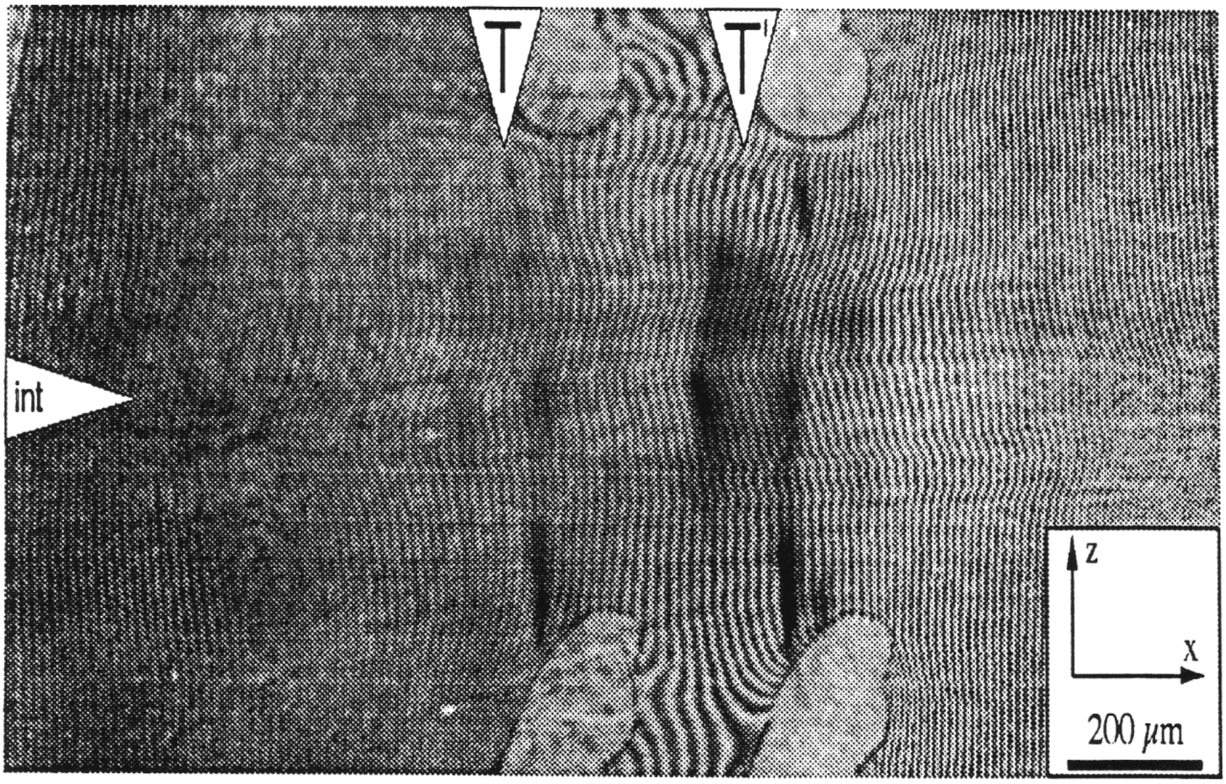

Fig. 8: interferogram of the plasma 300 ps after the interaction with the short pulse. The horizontal arrow shows the short pulse interaction axis. The vertical arrows show the original target position.

Conclusion

Optical interferometry with picosecond temporal resolution has been used to obtain a density map of millimetre sized plasmas produced by symmetrical laser heating of a thin target. Significant improvements in the density characterisation of the plasma have been introduced by the high temporal resolution and appropriate target design. The plasmas thus produced and characterised appear to be most suitable for interaction studies. The uniformity and symmetry of the plasma was confirmed by the substantial agreement between the experimental 2-D density maps and 2-D hydrocode computational predictions.

In the second part of the experiment, the propagation of a ps laser pulse in a plasma preformed by irradiation of thin foil targets. The propagation of the pulse appeared to be strongly affected by the preformed plasma conditions, while in the investigated range seemed to be independent from the energy of the pulse itself. The short pulse energy fraction transmitted through the plasma was sensibly higher for heating energies above the threshold value 8 10^{13} W/cm^2. Cross section imaging also showed that above this threshold refraction effects became less severe. Density perturbations induced by the short pulse propagation were detected via interferometry.

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