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Characterization of laser plasmas for interaction studies: Progress in time-resolved density mapping

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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 characterization due to the use of a picosecond pulse probe is reported, and the relative merits of different target designs are also discussed. The two-dimensional density maps obtained appear to be in substantial agreement with two-dimensional hydrodynamic code predictions. [S1063-651X(96)08712-0]

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I. INTRODUCTION

Laser heating of thin targets is now recognized 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 a 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. Some of these methods are reviewed and discussed in a previous paper [6].

Among the diagnostics for plasma characterization, 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 [7,8] 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 as the fast ignitor scheme for ICF [9] and particle acceleration by plasma waves [10], 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 time scales, the use of probe pulses of comparable duration appears to be necessary. Microphotography with resolution of a few picoseconds has already been successfully used in the past to study the temporal evolution of laser produced plasmas [11]. The recent enormous advances in laser technology, and in particular the development of the chirped pulse amplification (CPA) technique [12], gave a new impulse to these diagnostics. The high power and coherence of the short pulses produced with this technique allow one to probe large plasma regions. Furthermore, since in short pulse interaction studies the probe is normally split off from the interaction beam, synchronization of probe and interaction pulse within a few pulse lengths can easily be obtained by optical delay.

In a previous work [6], we already produced and characterized 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 briefly 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 strips (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 two-dimensional (2D) 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

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not be characterized completely, since temperature measurements via K-shell line spectroscopy were not possible. Another problem encountered was the deviation of the plasma from cylindrical symmetry, as a consequence of the target design. This aspect was also discussed in Ref. [6]. 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 considerably 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 [6].

Since the plasma was produced with the aim of studying the propagation of a short laser pulse [13] from the Rutherford Appleton Laboratory 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 and (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 thin target configuration was employed in order to minimize perturbation of the cylindrical symmetry.

II. EXPERIMENTAL SETUP

The new experiment was performed at the Central Laser Facility of the Rutherford Appleton Laboratory. The plasma was produced by four 600 ps, 1.053 μm heating beams of the Vulcan laser, using the configuration reported in Ref. [6]. 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 $-13°$ 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 target 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 (see Ref. [6]). 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 mm. A modified Nomarski interferometer [14] was employed to detect the phase changes undergone by the probe beam and measure the electron density profiles. The probe line setup was different from the configuration of the previous experiment. A confocal optical system (composed of a microscope objective and an $f/10$ 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 Wollanston prism was located close to this plane.

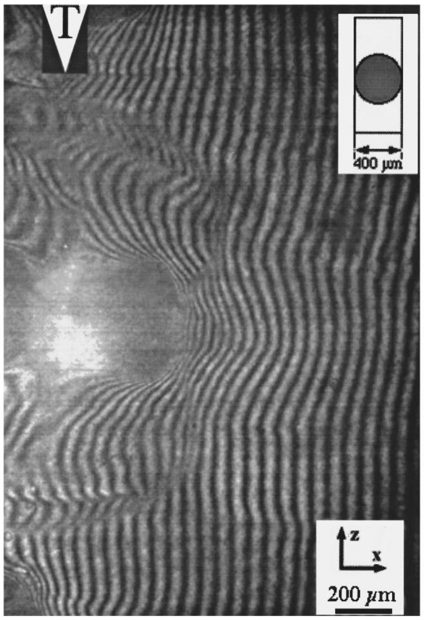

FIG. 1. Interferogram taken 3 ns after the peak of the heating pulses using a 100 ps probe pulse. The target was an Al disk (400 μm diameter) on a narrow plastic strip. The heating irradiance was 5×10^{13} W/cm^2 on each side of the target. The original target position is shown by a T wedge.

III. DENSITY MAPPING

As stated before, when the plasma was characterized 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 3.0 ns after the peak of the 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. As pointed out in Ref. [6], 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 a heating irradiance comparable to the case of Fig. 1. The improvement in the interferometric characterization 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 vis-

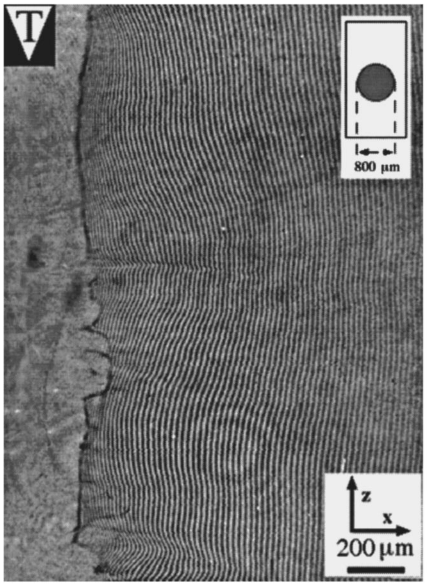

FIG. 2. Interferogram taken 2 ns after the peak of the heating pulses using a 1 ps probe pulse. The target was an Al disk (800 μm diameter) on a large plastic foil. The heating irradiance was 7×10^{13} W/cm^2 on each side of the target.

ibility 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 center 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 [15] 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 [6]. The algorithm proposed by Barr [16] was used this time to invert the Abel integral. The phase distribution and the 2D density map obtained from the interferogram of Fig. 2 are shown in Fig. 3.

The hydrodynamic expansion of the plasma was simulated using the 2D Eulerian hydrocode POLLUX [17]. The code models laser absorption via inverse bremsstrahlung and thermal transport via flux-limited Spitzer-Harm conductivity. Ionization is calculated assuming local thermodynamic equilibrium, 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. 4 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, confirm-

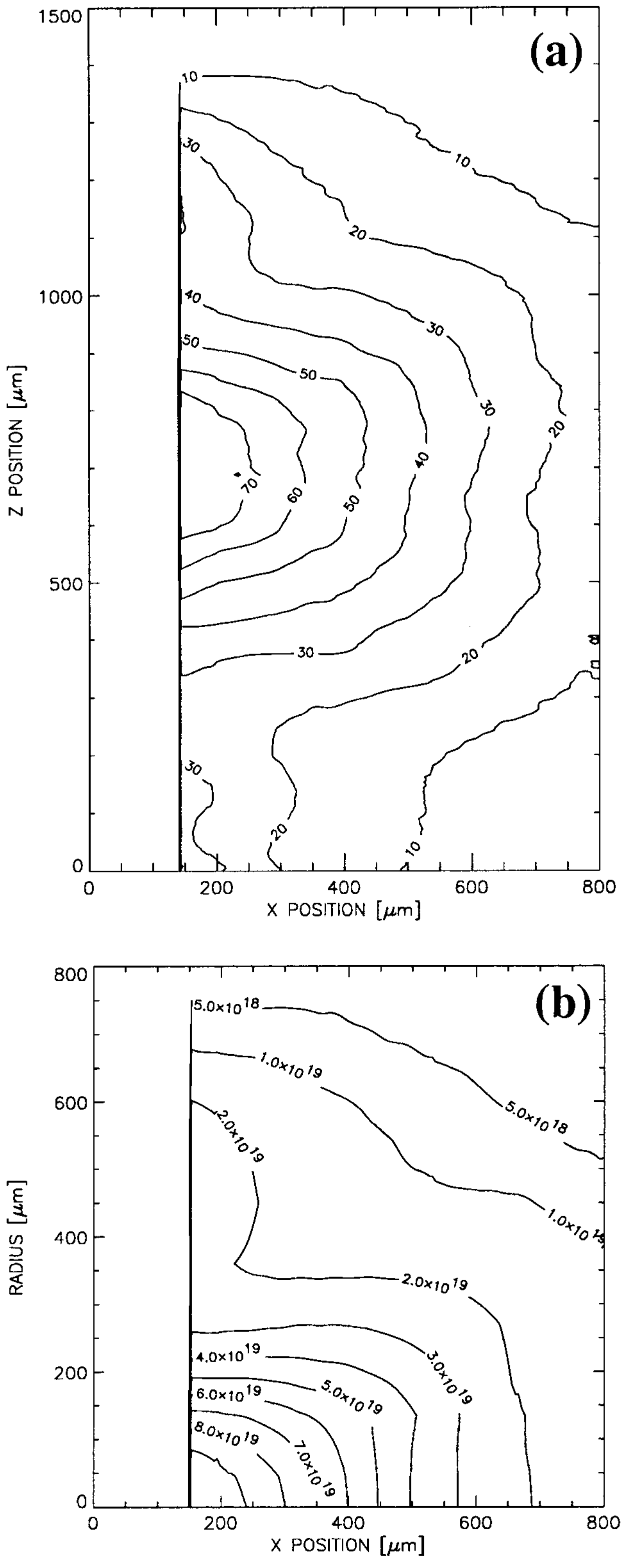

FIG. 3. (a) Phase map obtained from the interferogram of Fig. 2, using a Fourier transform method. The phase is expressed in radiants. The X position is measured with respect to the original target position, while the origin of the Z position is arbitrary. (b) Density map obtained by Abel inversion of the phase map. The density is expressed in electrons/cm^3. The radius is measured with respect to the symmetry axis.

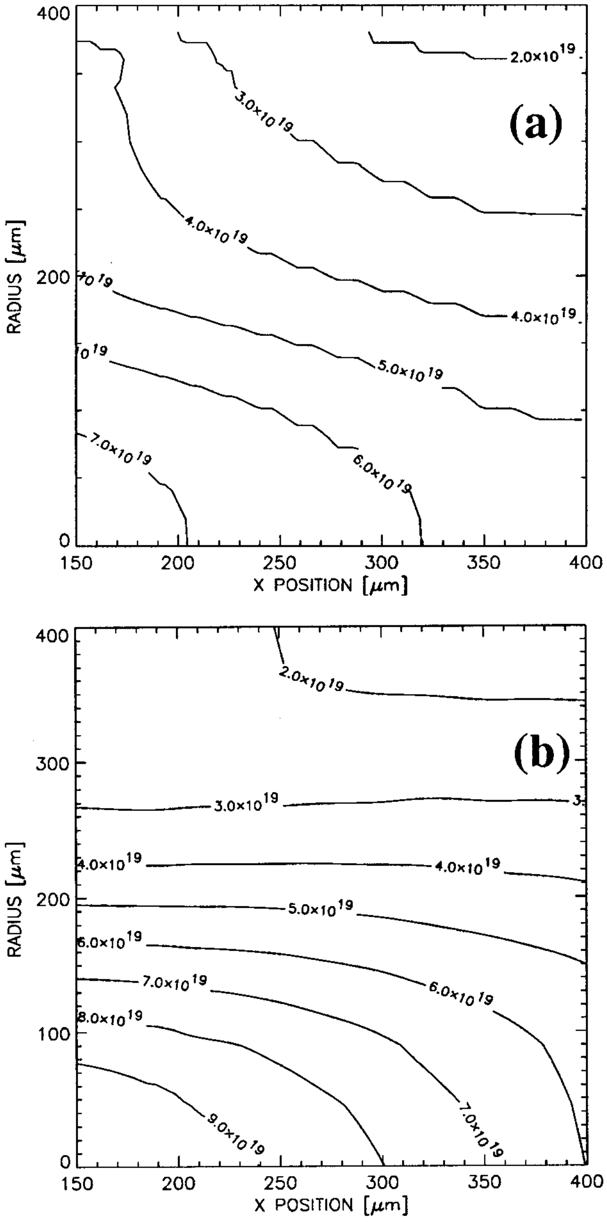

FIG. 4. (a) 2D simulation for the density profile in the experimental condition of the interferogram of Fig. 2. (b) Experimental profile for comparison.

ing that the assumption of cylindrical symmetry is justified for plasmas produced with the new target configuration. The residual, though unsubstantial, 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 modeled 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 an X-shaped target is shown in Fig. 5. Unfortunately the width of the Al arms could not be reduced below 200 μm, 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.

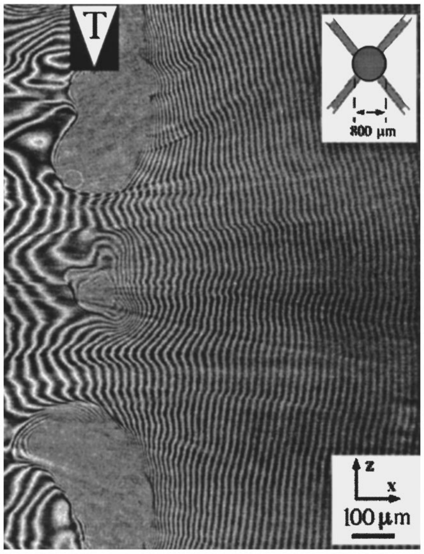

FIG. 5. Interferogram of a plasma produced from a X-shaped target, taken 2.2 ns after the peak of the heating pulses using a 1 ps probe pulse. The heating irradiance was 5×10^{13} W/cm^2 on each side of the target.

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. This aspect was discussed in detail in Ref. [6]. Here we only notice that these conclusions can now be extended over almost the whole plasma extent, thanks to the progress in the plasma characterization outlined in the present paper.

IV. CONCLUSION

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

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[1] D. H. Phillion, E. M. Campbell, K. G. Estabrook, G. E. Phillips, and F. Ze, Phys. Rev. Lett. **49**, 1405 (1982).
[2] R. A. London and M. D. Rosen, Phys. Fluids **29**, 3813 (1986).
[3] J. P. Christiansen, D. E. Ashby, and K. V. Roberts, Comput. Phys. Commun. **7**, 271 (1974); R. W. Lee, L. Whitten, and R. E. Stout II, J. Quantum Spectrosc. Radiat. Transfer **32**, 91 (1984).
[4] D. L. Matthews *et al.*, Phys. Rev. Lett. **54**, 110 (1985).
[5] W. Seka, R. E. Bahr, R. W. Short, A. Simon, R. S. Craxton, D. S. Montgomery, P. E. Young, K. Estabrook, W. L. Kruer, and T. W. Johnston, Phys. Fluids B **3**, 448 (1991).
[6] L. A. Gizzi, D. Giulietti, A. Giulietti, T. Afshar-Rad, V. Biancalana, P. Chessa, C. Danson, E. Schifano, S. M. Viana, and O. Willi, Phys. Rev. E **49**, 5628 (1994); **50**, 4266(E) (1994).
[7] P. E. Young, J. H. Hammer, S. C. Wilks, and W. L. Kruer, Phys. Plasmas **2**, 2825 (1995); P. E. Young, M. E. Foord, J. H. Hammer, W. L. Kruer, M. Tabak, and S. C. Wilks, Phys. Rev. Lett. **75**, 1082 (1995).
[8] P. E. Young, Phys. Plasmas **2**, 2815 (1995).
[9] M. Tabak, J. H. Hammer, M. Glinsky, W. Kruer, S. Wilks, J. Woodworth, E. Campbell, and M. Perry, Phys. Plasmas **1**, 1626 (1994).
[10] E. Esarey, P. Sprangle, J. Krall, and A. Ting, IEEE Trans. Plasma Sci. **24**, 252 (1996).
[11] S. Ariga and R. Sigel, Z. Naturforsch. **31a**, 697 (1976); A. G. M. Maaswinkel, R. Sigel, H. Baumhacker, and G. Brederlow, Rev. Sci. Instrum. **55**, 48 (1984).
[12] P. Maine, D. Strickland, P. Bado, M. Pessot, and G. Mourou, IEEE J. Quantum Electron. **QE-24**, 398 (1988).
[13] A. Giulietti, M. Borghesi, C. Danson, D. Giulietti, L. A. Gizzi, A. Macchi, and D. Neely, in *Ultrafast Processes in Spectroscopy*, edited by O. Svelto, S. DeSilvestri, and G. Denardo (Plenum, New York, 1996).
[14] R. Benattar, C. Popovics, and R. Sigel, Rev. Sci. Instrum. **50**, 1583 (1979).
[15] M. Takeda, H. Ia, and S. Kobayashi, J. Opt. Soc. Am. **72**, 156 (1982).
[16] W. L. Barr, J. Opt. Soc. Am **51**, 943 (1961).
[17] G. J. Pert, J. Comput. Phys. **43**, 111 (1981); R. Taylor (private communication).