Interferometric measurement of preheating in laser shocks

Dimitri Batani and Fabrizio Giugliano
Dipartimento di Fisica ''G. Occhialini'' and INFM, Università di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy

Tom Hall
University of Essex, Wivenhoe Park, Colchester, C04 3SQ, United Kingdom

Michel Koenig
LULI, CNRS, Ecole Polytechnique, 91128 Palaiseau, France

(Received 20 November 2000; published 20 September 2001)

We present a preliminary study of preheating in laser shocks using an interferometric diagnostic. A low energy probe laser divided in two by a biprism produces an interference pattern on the rear side of a target. The expansion due to preheating causes a fringe shift before shock arrival. A streak camera produces time-resolved images of the target rear side, which are filtered to reduce noise and correct for instrumental effects. Results are compared with an analytical model, which assumes that preheating is due to x rays, and with results from reflectivity measurements.

DOI: 10.1103/PhysRevE.64.047401 PACS number(s): 52.35.Tc, 52.50.Jm, 52.70.−m

I. INTRODUCTION

Laser shock experiments are performed to create high pressures ($\geqslant$10 Mbars) in materials. When a high energy laser irradiates a solid, its surface layers are converted into a plasma and a shock is generated and propagates into the target compressing it.

Preheating is a process in which the x rays (or hot electrons) generated in the plasma corona heat matter ahead of the laser shock. The measurement and understanding of this process is a topical subject in inertial confinement fusion where fuel preheat can significantly reduce the degree of compression and pellet yield that can be achieved [1]. Preheating control is also important in equation of state (EOS) measurements [2] with laser shocks [3]. In this context, a high level of preheating is unwanted since the shock propagates in a medium whose parameters (density, pressure, internal energy) become undetermined and Hugoniot-Rankine relations can no longer be used to get EOS data.

Previous studies [4,5] of preheating used different approaches. The emission of the target rear side has been recorded and the temperature estimated with the hypothesis of black body emission as *brightness* or *color* temperature. Alternatively the temporal shape of the signal (and in particular the appearance of an early emission before shock breakout) has been related to preheating. Recently, Benuzzi *et al.* [6] have studied preheating using the reflectivity of the target rear side. We used this diagnostic for comparison with the results obtained with the method presented in this paper.

Here we present a preliminary study of preheating based on an interferometric diagnostic: an interference pattern is created on the rear side of a target. Preheating causes a shift of the fringes due to expansion of the x-ray heated rear face and we measure the fringe shift velocity. The final part of the paper compares the results to a simple analytic model, which estimates the preheating temperature by quantifying the x-ray intensity for a certain laser energy and target thickness.

II. EXPERIMENT SETUP

Figure 1 shows the setup. The experiment was done at the Laboratoire pour I'Utilisation des Lasers Intense (LULI). Targets were irradiated with a $\lambda = 0.53\ \mu$m Gaussian-shaped drive pulse with a full width half maximum (FWHM) $\approx$600 ps. The laser was smoothed with phase zone plates (PZP) [7,8]. The optical system (PZP and focusing lens) produced a focal spot of $\approx$350 μm FWHM with a central flat region of $\approx$200 μm diameter giving spatially averaged intensities $\approx 5\times10^{13}$ W/cm^2.

The diagnostic consisted of a frequency doubled ($\lambda = 0.53\ \mu$m) probe beam, which irradiates the rear side of the target at 45°. Before reaching the target, the probe was divided into two parts by a BK7 glass biprism ($n = 1.519$ at $\lambda = 0.53\ \mu$m, wedge angle $\beta = 2°$). The two waves coming out of the biprism created an interference pattern on the target rear face, which was imaged on a visible streak camera and was spatially and temporally resolved. The probe beam was Gaussian in time with FWHM$\approx$600 ps and an intensity on target $\approx 2\times10^5$ W/cm^2. The spatial resolution of the streak camera was 7 μm on target and the temporal resolution was 10 ps. The interfringe distance l is given by

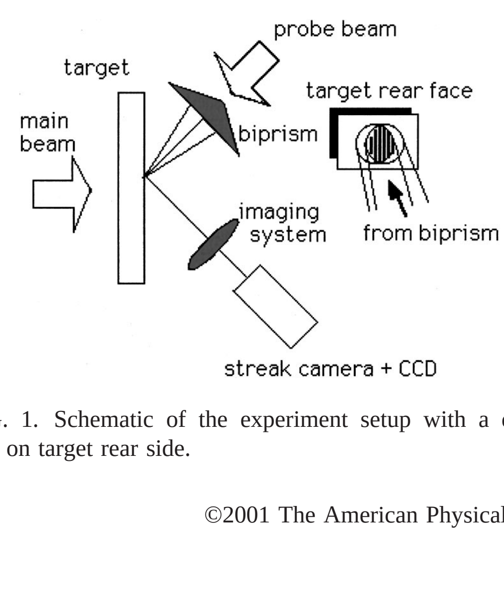

FIG. 1. Schematic of the experiment setup with a detail of fringes on target rear side.

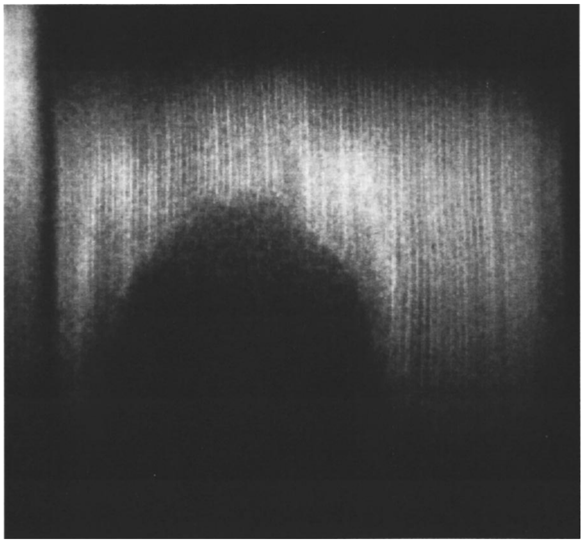

FIG. 2. Images obtained with the diagnostic described in Sec. II. The target was 13.74 μm aluminum and the laser energy 36.4 J($I \approx 4\times 10^{13}$ W/cm^2). Time is on the vertical axis and flows from top to bottom. Space is horizontal. The dimensions of the picture are 800 μm$\times$1.9 ns. The signal on the left is a time fiducial: a part of the incoming laser beam is sent onto the streak camera slit and synchronized so to give the laser arrival time on target front side. The laser pulse is Gaussian with FWHM of 600 ps. The time from arrival of laser pulse maximum to shock breakout on target rear side can be measured on the image and is ≈450 ps, in agreement with simulations with the code MULTI [10].

$$l=\frac{\lambda}{\sqrt{2}(n-1)\tan\beta} \tag{1}$$

It is expected that the higher the preheating, the larger the fringe shift velocity caused by target expansion, i.e., the interference fringes shift more rapidly when laser energy increases and target thickness decreases.

An additional contribution to the phase shift may come from the evaporation of material (mainly hydrocarbides absorbed on target surface), due to heating, in front of the target rear face, creating a vapor atmosphere with a refractive index that affects the optical path and interference conditions.

The targets were simple aluminum or aluminum coated with plastic (CH) on the front side (that directly irradiated by the main laser). These were used to minimize the preheating because of the low x-ray flux produced with plastic [6,9].

III. EXPERIMENTAL RESULTS AND IMAGE PROCESSING

Figure 2 shows one image obtained with our diagnostic: we notice the interference fringes. The reflectivity of the target rear face decreases abruptly when the shock breaks out.

All the images were affected by aberrations due to the streak camera, especially at the photocathode edges, and by random noise. To increase fringe visibility, it was necessary to filter this noise. The filtering method was quite simple and was performed only on the central part of the images as shown in Fig. 3. There are two reasons for analyzing the central selection of each image only: first, this region of the photocathode of the streak camera is less affected by aberrations and, second, only in the central part of the shocked region, corresponding to planar shocks and flat irradiation, the laser intensity is precisely known.

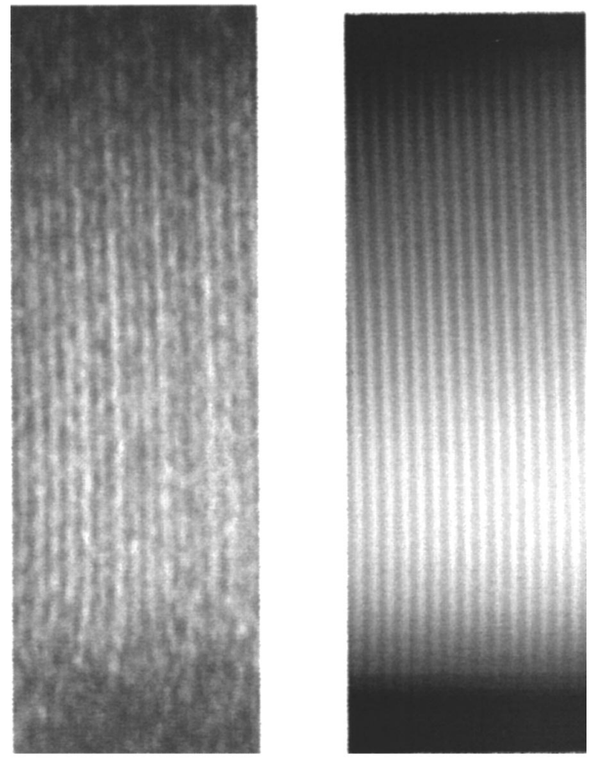

FIG. 3. Central selection of Fig. 2. (a) Streak camera image. (b) Reconstruction after noise filtering. The fringe shift is more evident and measurable. Time is on the vertical axis and flows from top to bottom. Space is horizontal. The dimensions of the picture are 200 μm$\times$600 ps.

At each time we approximated the luminosity signal on the streak camera with a sinusoid. The parameters used in the fit were the amplitude and the phase of the sinusoid and the background level. The interfringe distance was fixed and kept constant over the whole image [it was also measured to fairly correspond to that given by Eq. (1), $l=20$ μm]. Figure 3(b) shows the reconstructed image: the temporal fringe shift is more evident than in the unprocessed image [Fig. 3(a)].

Figure 4 shows the phase displacement $\Delta\phi$ vs time. It also shows the displacement on a reference shot, i.e., a shot in which the main laser beam was not fired. The constant slope measured here is an instrumental effect due to the streak camera and must be subtracted to the experimental results to obtain the real fringe shift $\Delta\phi$ due to preheating. At early times, the total shift measured on a shocked targets can also be approximated with a constant slope. Later we see a reversal in phase shift. The instrumental slope was ≈17 mrad/ps. In the case in Fig. 4, the subtraction of such instrumental slope gives a phase displacement of 12 mrad/ps; only, this is due to preheating.

Results obtained in a previous work with a different diag-

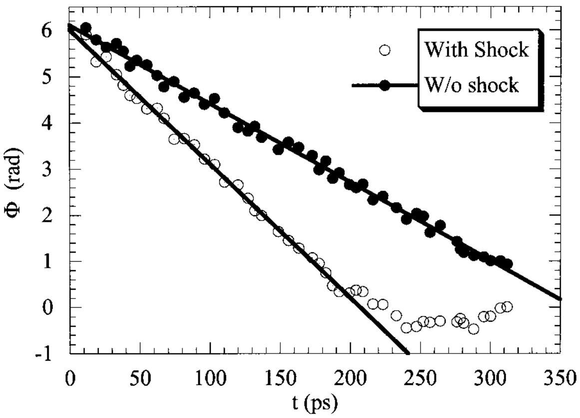

FIG. 4. Fringe shift vs time. Filled circles indicate the fringe phases on images without shock. The angular coefficient is the fringe shift velocity. Phases with shock were obtained analyzing the image in Fig. 3.

nostic [6] suggest that in our case, preheating may affect the target rear face already ≈1 ns before shock breakout. This means that, first, when the probe beam begins to enlighten the rear face, preheating is already active (probe FWHM ≈600 ps) and, second, the final reversal in the shift is not due to preheating for its short duration [6].

We performed the analysis of the images obtained with different laser energy and target thicknesses and composition (see Table I). In particular, a thin plastic layer coating (≈1 μm) on the laser side minimized preheating because of the low x-ray flux produced in plastic. All the values of the phase shift velocity $\Delta\phi/\Delta t$ are reported after subtraction of the instrumental slope (17 mrad/ps).

IV. COMPARISON WITH REFLECTIVITY

Table I also gives a comparison between measured data and the preheating temperature T_R obtained with the reflectivity diagnostic described by Benuzzi *et al.* [6].

This is based on the fact that an increase in temperature produces a drop in Al reflectivity before shock breakout, which can be measured from streak camera images like that in Fig. 2 (the part of the laser reflected on the lateral unshocked region of the target is used as reference). Both T_R

TABLE I. Comparison between experimental and calculated results: $\Delta\phi/\Delta t$ has been measured, T_A calculated with Eq. (3), and T_R obtained with the reflectivity diagnostics described in Ref. [6].

E_L (J)	d Al (μm)	$\Delta\phi/\Delta t$ (mrad/ps)	T_A (eV)	T_R (eV)
24.7	A l7.3 CH 1	3.0±1.2	0	0
27	13.74	5.6±1.1	0.79	0.3
32.7	13.74	8.0±0.8	0.96	0.55
33.7	13.74	7.4±1.3	0.98	0.5
34	13.74	7.7±0.7	1.01	0.45
36.4	13.74	12.1±0.7	1.15	1.0
34.6	12.58	10.3±1.8	1.48	1.55

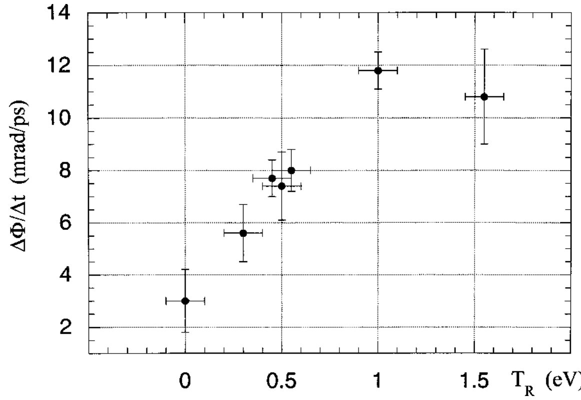

FIG. 5. Phase displacement reflectivity temperature.

and $\Delta\phi/\Delta t$ in Table I are given just before shock breakout.

Figure 5 shows fringe shift velocity as a function of preheating temperature. Considering the experimental error bars, this is compatible with a monotonic increase of $\Delta\phi/\Delta t$ vs preheating, and means that a larger shift really corresponds to higher preheating.

V. THE ANALYTIC MODEL

A simple analytic model allowed to evaluate preheating by quantifying the x-ray intensity in laser-plasma interaction. After Löwer *et al.* [4], the preheating temperature produced by photons with energy $h\nu$ is

$$T(\nu,z)=S(\nu,z)\frac{\tau\mu(\nu)}{\rho C_V}, \quad (2)$$

where $S(\nu,h)$ is the x-ray intensity at distance z inside the target, τ is the x-pulse duration (of the order of the laser pulse), μ is the material absorption coefficient, ρ is the mass density (2.7 g/cm^3 for Al), and C_V is the specific heat. Evaluating S as a function of laser energy, we finally obtain for the preheating temperature of target rear side,

$$T_A=\frac{E_L\mu\alpha\eta e^{-\mu d}}{\pi R^2\rho C_V}, \quad (3)$$

where η is the x-ray conversion efficiency, πR^2 is the focal spot area, and d is the target thickness. In passing from Eqs. (2) to (3), we approximated the spectral function $S(\nu)$ with a single peak corresponding to the maximum of x-ray emission for the considered material (Al or CH). Then μ is the mass absorption coefficient at the peak photon energy. For Al, looking at data in the literature (Ref. [9] in particular), we assumed the peak to be at ≈1.56 keV and $\eta\approx5\%$. Actually the values found with Eq. (3) must be considered approximate because of the great uncertainty in the parameters involved. However, as can be seen in Table I, the calculated temperatures are in fair agreement with those obtained by reflectivity (quantitatively the difference is within ≈2).

VI. CONCLUSIONS

A simple interferometric diagnostic was developed for the evaluation of preheating of the rear side of shocked targets. Results, although preliminary, seem to agree quite well with those obtained with an independent diagnostic based on reflectivity measurements. The sensitivity of the method appears to be quite high: at early times with respect to shock breakout, a fringe shift is measured even when no appreciable change in reflectivity is observed.

Unfortunately the method is very sensitive to noise and to streak camera aberrations, so it requires image filtering before data can be analyzed. Also the initial phase of fringe shift, corresponding to the beginning of rear side preheating, was not observed due to the short duration of the probe pulse. Hence it would be interesting to repeat the experiment with a longer pulse and also exploring a wider range of target materials and laser energies. Comparison with the results of a simple model shows that target preheating is due to x rays produced on the front side of the target. This is also confirmed by the fact that CH coated targets showed a very small fringe shift. Another problem of this diagnostic method is that in order to have sufficient sensitivity, a small fringe separation (short l) is needed, but such small fringes are difficult to image with the sufficient spatial resolution.

At late times a reversal of fringe shift is observed, just after shock breakout. The time duration of this phenomenon corresponds to the rapid drop in reflectivity observed in previous works [6] and is too rapid to be connected with preheating. We think that it may arise due to the creation of a rarefaction wave in the solid starting on the target rear side and traveling back into the material at sound speed, as explained in Zeldovich and Raizer [2]. Also, the final reversal in shift may be due to the contribution of the evaporated material in front of the rear face: during the preheating phase and before shock breakout this is made by a gaseous atom atmosphere (with refractive index $n>1$), while after shock breakout this will be a real plasma (with plasma electron giving a refraction index $n<1$).

ACKNOWLEDGMENTS

This work was supported by the E.U. ''Access to Large Scale Facilities'' Programme. We acknowledge useful discussions with S. Bittanti and F. Previdi, Politecnico di Milano, Italy, and A. Benuzzi, LULI.

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