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A simple technique for laser-induced ablation pressure measurement

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Abstract. A simple method for measuring laser-induced ablation pressure is described. The technique utilizes the well-known double foil concept. In the present experiment the impact times were estimated by monitoring the reflectivity of the impact foil rear. The measurements were performed using a glass laser ($1 \cdot 06\,\mu m$ wavelength) in the 10^{11}–10^{13} W/cm^2 irradiance range. Experimental results showed good agreement with those obtained using other techniques as also those with the self-regulating ablation model prediction.

Keywords. Double foil; impact time; probe beam reflectivity; laser-induced ablation pressure.

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1. Introduction

Fuel compression along a low adiabat is one of the important requirements of laser-induced fusion (Nuckolls *et al* 1972). High fuel compression can in principle be achieved by symmetrically imploding a spherical pellet containing fusionable material (Nuckolls *et al* 1972). High pressures needed for pellet implosion can be obtained by laser-induced ablation of the pellet surface (Daiber *et al* 1966; Nuckolls *et al* 1972). Pressures in excess of 70 Mb have been estimated in various experiments (Ahlborn *et al* 1982; Amiranoff *et al* 1986). There are several methods available for measurement of ablation pressure. These are either based on ablation parameter measurements like mass ablation rate, plasma expansion velocity and momentum of the ablating plasma (Decoste *et al* 1979; Ripin *et al* 1980; Grun *et al* 1981; Daido *et al* 1983; Grun *et al* 1983), target terminal velocity measurements using rear cone calorimetry (Eidmann *et al* 1984; Shirsat *et al* 1986), optical (Grun *et al* 1983; Eidmann *et al* 1984; Dhareshwar *et al* 1985) or X-ray shadowgraphy (Key *et al* 1980; Raven *et al* 1981; Obenschain *et al* 1983) and time-resolved streak record of the visible emission for the rear surface of the impact foil (Obenschain *et al* 1981; Cottet *et al* 1985). In this paper we report another method which is simpler than those in use and provides results with reasonably good accuracy.

2. Experiment

Experiments were performed with a 15 Joule, 5 ns Nd: glass laser. The beam was focussed at the target surface using an aspheric lens of focal length 50 cm. Target and impact foils were parallel to each other with known separation and were placed at the centre of an evacuated plasma chamber. A fraction (8%) of the incident energy was made to reflect using a beam splitter and the same was collected on the energy meter in order to estimate the incident laser energy. The experimental set-up is shown in figure 1. A He-Ne beam was used as a probe and was incident at an angle of 10° to the target normal on the highly reflecting impact foil rear. The reflected beam from the undisturbed rear surface was collected on a photo diode (type HP 5082–4200) through an aperture of 10 mm diameter and a focussing lens of small focal length. The d.c. signal was fed to a storage oscilloscope. When triggered externally in single sweep mode using a fraction of the glass laser pulse, a steady probe signal was recorded on the oscilloscope. A red filter (type Corning OY-1) was used in front of the photo diode to cut off the plasma luminosity. A steady light signal was thus recorded on the oscilloscope. The target (front foil, exposed to the laser) and impact (rear) foils were of 6 μm and 12 μm thick aluminum respectively. Spacing between the foils was varied from 400 μm to 1200 μm. The target was placed in the near field of the focussing lens. The choice of focal spot diameter (full width at half maximum) at the target surface was varied between 150 μm and 350 μm. Smaller focal spots were not used in order to avoid possible edge effect (Ripin *et al* 1980). Intensity at the target surface was varied by changing the focal spot diameter at a constant laser energy and by using suitable neutral density filters for a fixed focal spot diameter.

Intense laser radiation ablates the material in the focal spot region. The ablating plasma exerts a high ablation pressure on the remaining target foil. This pressure is responsible for the inward motion of residual target. The bulk of this dense target matter after traversing the distance between the target and impact foil collides with the front surface of the impact foil creating a shock in it. The shock wave unloads at the rear surface after travelling through the impact foil spoiling its reflectivity and causing a fall in the steady photo-diode signal (figure 2). The reflectivity fall is attributed to the cold dense plasma formed at the shock breakout time. The plasma intensively absorbs the probe radiation.

In our experiment a small amount of the laser light scattered off from the target entered the detector and its peak location was found to be a suitable time marker signal for laser interaction with the target surface (figure 2). The fall time of the light detector system (peak to 90% of the signal) is about ≈ 1 ns. Since we are interested only in the instant of the impact, the initial fall of the reflectivity is of relevance. The delay time

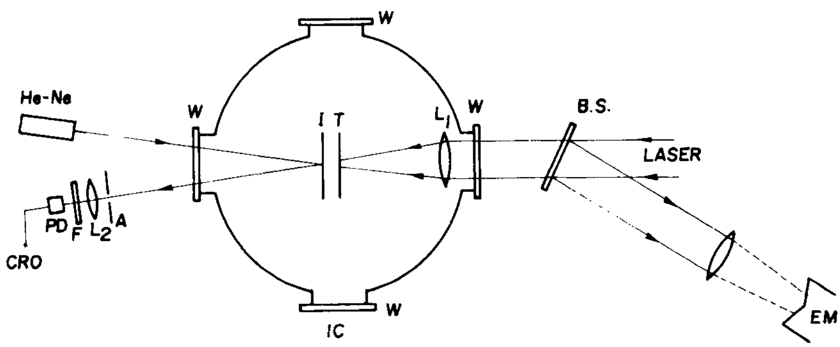

Figure 1. Schematic of experimental set up. A, aperture; BS, beam splitter; CRO, cathodo ray oscilloscope; EM, energy meter; He-Ne, probe beam I, impact foil; IC, interaction chamber; L_1, L_2, focussing lenses; PD, photo diode; T, target foil; W, glass window.

between laser pulse peak and the beginning of the fall of the reflected probe beam intensity has thus provided an estimate of the time required for the accelerated foil to cover the distance between the target and impact foils. This time is conventionally called impact time in double foil shadowgraphy technique. We have neglected the shock transit time ≈ 1 ns (Meyer and Thiell 1984). This assumption is justified as the flight time of the accelerated target compared to the shock transit time of the impact foil is much larger. The velocity was determined by plotting the impact time for various separations between target and impact foils and measuring the slope of the straight line thus obtained. The ablation pressure (P_A) was calculated by using a well-known rocket formula (Ripin *et al* 1980)

$$P_A = \rho t V/\tau,$$

where ρ, t, v and τ are target density, initial thickness, terminal velocity of the accelerated foil and acceleration time respectively. The acceleration time was chosen to be equal to the laser pulse duration. The above mentioned relation assumes ablation thickness Δt negligible compared to the original target thickness t. However at high laser intensities, ablated thickness must be subtracted from the original target thickness while calculating the ablation pressure. The estimates of the ablated target thickness were taken from our earlier work (Shirsat *et al* to be published). However, for absorbed laser intensities $\leqslant 5 \times 10^{12}$ W cm^{-2} it was found to be much smaller than t and therefore neglected. For 5×10^{12} and 10^{13} W cm^{-2} absorbed laser intensity it was estimated to be 0·8 μm and 1·2 μm respectively. Above 5×10^{12} W cm^{-2} the corresponding values of ablation thickness have been included in the calculations. It is noticed that the probe reflectivity falls very slowly as in figure 2. This happens because the He-Ne probe spot diameter at the target rear is about 750 μm and the shock breakout takes place in a small area of the foil (equal to main laser spot size). Thus, the reflectivity of the initially undisturbed target rear falls slowly. However the shock breakout time is clearly seen.

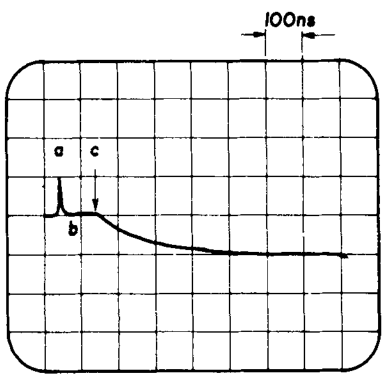

Figure 2. Oscilloscope signal; a. Marker pulse due to laser light.; b. Steady signal due to He-Ne laser; c. Instant of reflectivity fall of the impact foil rear. Target and foil separation 400 μm.

3. Discussion

As can be seen from figure 3, the absolute magnitude as well as scaling of ablation pressure (P_A) with absorbed laser irradiance (I_A) obtained using the present method, is in good agreement with the self-regulating ablation model (Puell 1970). Magnitudes of the measured ablation pressure in our experiment agree well with those obtained using other techniques in different laboratories such as Faraday collector method (Decoste *et al* 1979; Ripin *et al* 1980; Grun *et al* 1981; Eidmann *et al* 1984; Meyer and Thiell 1984), ballistic pendulum (Grun *et al* 1983), rear cone calorimeter (Eidmann *et al* 1984; Shirsat *et al* 1986) and optical shadowgraphy (Grun *et al* 1983; Eidmann *et al* 1984; Dhareshwar *et al* 1985). To provide a comparison, figure 3 also contains some results obtained by various other techniques.

Although the technique appears to provide data which compare reasonably well with theory and those obtained using other methods, it is worthwhile to compare it with other methods and discuss its limitations. There are several methods for determination of ablation pressure. Five of them can be regarded important as they have been widely used. As mentioned earlier they are (i) Faraday cup collectors array

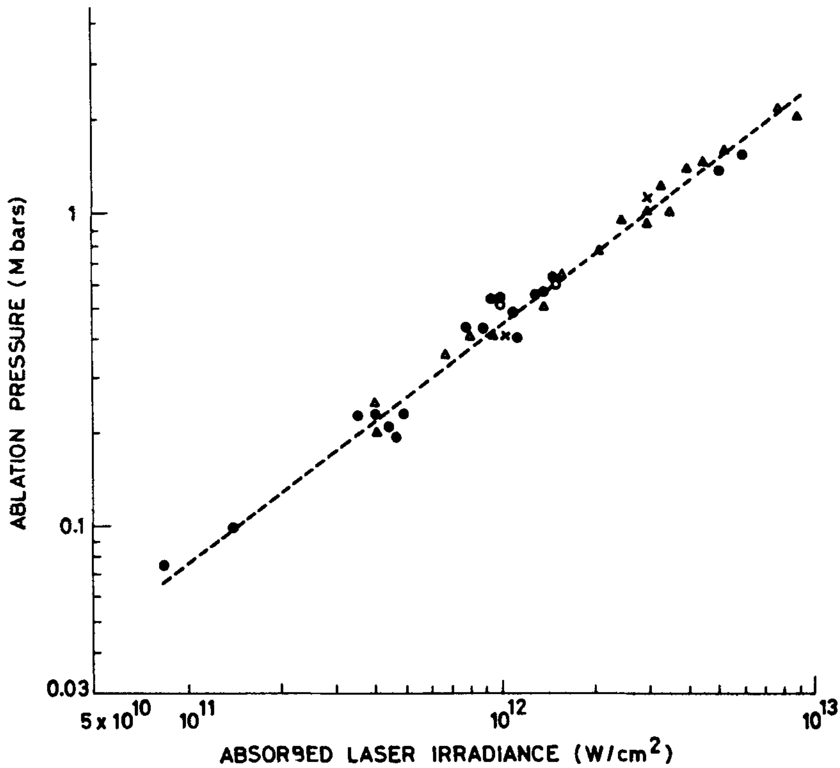

Figure 3. Variation of ablation pressure with absorbed laser irradiance. Present experiment (●); ballistic pendulum (X) (Grun *et al* 1983); near cone calorimetry (△) (Eidmann *et al* 1984; Shirsat *et al* 1986); optical shadowgraphy (○) (Grun *et al* 1983; Eidmann *et al* 1984 and Dhareshwar *et al* 1985) and mass ablation rate/ablation velocity (▲) (Grun *et al* 1983; Meyer and Thiell 1984). Dotted line indicates the theoretical prediction using the self-regulating model.

with or without energy calorimeter arrays; (ii) ballistic pendulum arrays; (iii) ballistic pendulum as a target; (iv) optical or X-ray shadowgraphy and (v) streak record of visible emission from the rear surface of the impact target.

In the first method (Decoste *et al* 1979; Ripin *et al* 1980; Grun *et al* 1981, 1983; Daido *et al* 1983) one measures average velocity perpendicular to the target ($v_\perp$) surface and mass ablation rate or momentum perpendicular to the target ($P_\perp$). Ablation pressure can then be calculated by $m^0\ v_\perp$ product or dividing specific momentum ($P_\perp$) by laser pulse duration, where m^0 corresponds to the mass ablation rate. The technique is lengthy and elaborate and requires curve fitting to obtain an accurate spatial distribution of velocity and momentum. The Faraday cups have to be built to ensure correct charge collection and energy calorimeters to ensure complete energy deposition of the ablated plasma. Charge state of the expanding plasma also has to be known for calculations. It has also been shown that the results are affected if different approaches of calculation are used. A detailed discussion of this aspect is given in Gupta *et al* (1987). Ballistic pendulum array is also used to measure $P_\perp$, via angular distribution of the ablated plasma momentum. In this approach one has to know the reflection of the ablated plasma striking the collector of the pendula. Thus a careful calibration is needed. The diagnostic also occupies a good fraction of the interaction chamber. When the ballistic pendulum is used as a target, the results are known to be unreliable as the late effects of target evaporation also get integrated in the target motion, giving false high momentum ($P_\perp$) transfer and hence high ablation pressure (Grun and Ripin 1982).

Optical shadowgraphy (Grun *et al* 1983; Eidmann *et al* 1984; Dhareshwar *et al* 1985) with double foil arrangement requires a short optical pulse well synchronized with the main laser pulse. The method offers a good time resolution but in order to estimate the correct impact time of the foils, one has to use several laser shots under identical experimental conditions. This problem can be overcome by using a high speed streak camera, a rather expensive device. One important point is that while working with IR lasers like CO_2, it is not possible to derive an optical probe from the main laser. Thus one has to use an additional well-synchronized short pulse visible laser.

X-ray shadowgraphy requires a laser produced short pulse X-ray source and X-ray imaging system to record the target foil motion and its collision with the impact foil. This method also needs multiple laser shots unless an X-ray streak camera is used. Thus shadowgraphy technique is not very simple though it may offer a reliable data. Streak record of the visible emission from the impact foil rear provides a better time resolution. However, the experimental requirements are expensive (Cottet *et al* 1985).

The present technique has certain limitations. These may arise due to 3-D expansion of the accelerated foil, if the distance between the target and the impact foil is large compared to the laser focal spot at the target surface and also the lack of time resolution if the target and impact foils are placed close to each other. 3-D expansion arises due to the fact that the detached, accelerated foil is free to expand laterally during its motion. This expansion may lead to an erroneous evaluation of the terminal velocity of the accelerated foil. The worst situation may arise when the focal spot diameter at the target foil is much smaller compared to the target foil separation. In our experiments the large spot diameter ($\approx 300\,\mu$m) and lower foil separation ($\approx 600\,\mu$m) do not pose a serious problem (Ripin *et al* 1980). However, even for small focal spot diameter ($\approx 150\,\mu$m) and large separation ($\approx 1000\,\mu$m), on axis velocity does not seem to be affected. It may be concluded from a reasonable estimate of ablation pressure at absorbed intensity $\approx 10^{13}$ W cm^{-2} (figure 3). This is perhaps due to the fact that during the acceleration phase, radial rarefaction wave starting from the outer edge of the foil does not disturb most of the detached foil. The rarefaction wave velocity Cs being $(Z\,KT\,M^{-1})^{1/2}$, where Z is the ion charge, KT the electron temperature and M the ion mass of the foil. During acceleration phase the temperature is ≈ 1 eV (McLean *et al* 1980) and $Z \approx 1$ (Shearer and Barnes 1971). Thus for a given aluminum foil Cs $= 2 \times 10^5$ cm sec^{-1}. The radial rarefaction wave would travel only 10 μm in to the target foil during the acceleration phase. This is small compared to the detached foil radius (80 μm). Thus the foil acceleration remains unaffected during laser ablation. However, lateral expansion at the edges will become important at later times but not before the foil has acquired its final velocity at the end of the laser pulse. Since the central part of the foil motion remains free from lateral expansion (Grun *et al* 1983), it meets and disturbs the impact foil along the axis and provides a correct estimate of the target final velocity. Since we are interested in this velocity, our estimate of ablation pressure remains reasonably correct.

The most ideal situation for this technique would be when a larger laser target interaction area is used. A laser spot as large as 1500 μm in diameter and moderate irradiance ($\leqslant 10^{14}$ W/cm^2) are increasingly being used these days to simulate proper laser plasma interaction conditions of fusion targets (Herbst and Grun 1981). The 3-D effects thus would not affect the results till the impact-to-foil separation is kept below 1000 μm with a laser focal spot of similar diameter. If the target preheat is kept low by using nanosecond laser pulse at moderate irradiance, the 3-D expansion of the accelerated foil can be kept further low. The typical time resolution in our experiment was 10%. This would mean an error of 10% in the ablation pressure. With a large laser spot diameter (≈ 1000 μm), 1000 μm foil separation and 10^7 cm/sec target velocity the impact time would be 10 nsec. It is possible to measure this time with an accuracy of 1 nsec. The technique is sensitive, as a slight impact on the impact foil can be detected via the reflected probe beam. To make it more sensitive a thinner impact foil can be used. Linearity will be only affected if 3-D effects start dominating either due to small laser spot or high intensity. In our experiment we were not able to notice appreciable 3-D effects. This is perhaps due to the fact that the accelerated foil was sufficiently cold due to low laser intensity and thick (6 μm) aluminum target.

4. Conclusion

We have presented a simple technique for pressure measurement in ablatively accelerated thin foil targets. The technique provides results which are in agreement with theory and those obtained using well-known methods. The approach has certain limitations but they can be overcome under suitable experimental conditions. However we would like to emphasize that the technique will be more suitable for experiments done with large spot irradiation, especially where a synchronous optical probe is not easily available like harmonic generation for CO_2 laser.

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