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Enhancement of ablation smoothing in laser-irradiated, high Z coated, thin foil targets

L J DHARESHWAR, P A NAIK and H C PANT
Laser Division, Bhabha Atomic Research Centre, Bombay 400085, India

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Abstract. An enhanced spatial smoothing of ablative motion of thin plastic foil targets coated with high atomic number ablators such as gold or aluminium, irradiated by a spatially modulated Nd : glass laser beam was observed. Optical shadowgraphy coupled with double foil technique was used to observe the laser-irradiated foil motion. Laser irradiance used for the experiments was in the range of 10^{11}–10^{13} watts/cm^2. A 60–80% enhancement in the smoothing was observed for a laser beam modulation (width 75–150 μm) at the target surface.

Keywords. Plasma; laser fusion; ablative compression; shadowgraphy; lateral transport.

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1. Introduction

A high implosion symmetry and a large hydrodynamic efficiency are two of the critical elements in achieving laser-driven pellet fusion (Bodner 1981). Whereas high laser-to-fuel coupling efficiency suggests shorter wavelength (Zimmerman 1974, 1979) symmetry requirements dictate a longer wavelength (Bodner 1981; Max *et al* 1981, 1982). Thus, an intensity-wavelength window has emerged on the scene of laser fusion scheme (Gardner *et al* 1981). To achieve a high gain, the symmetry of spherical target implosions has to be better than about 5% (Bodner 1981). In the absence of hydrodynamic instabilities, implosion assymmetry can arise due to non-uniform irradiation. However, these non-uniformities get partially smoothed out at the ablation surface due to classical lateral thermal diffusion in the conduction zone which increases with laser intensity (Obenschain *et al* 1981; Cole *et al* 1982) as well as with laser wavelength (Obenschain *et al* 1983). However, laser intensity cannot be indefinitely increased without generation of hot electrons and hard x-rays which can cause fuel preheat creating inefficient fuel compression. To achieve better implosion symmetry, suitably structured targets with low density foams have been suggested (Okada *et al* 1983). It has also been suggested that if the laser wavelength is gradually increased during the implosion, a more uniform compression can be achieved.

Recently it has been shown by x-ray backlighting technique, that, at 0·35 μm irradiation wavelength, there is considerable improvement in smoothing when a 0·5 μm gold coating is used over a 7 μm aluminium foil target (Bocher *et al* 1984). In the experiments described in our paper, we present results which indicate that for 1·06 μm irradiation wavelength, more than 80% smoothing in target motion is possible for a 75 μm (FWHM) intensity modulation in the laser intensity at the target plane, even in the moderate intensity range of 10^{12}–10^{13} W/cm^2 for gold (0·1 μm) coated 10 μm thick plastic targets.

2. Experiments

The main laser used for irradiation of the target foils was a 10 J, 5 n sec Nd : glass laser at a wavelength of 1·06 μm. The laser beam was focused on the target using a f/6 spherical lens to obtain a spot diameter of 350 μm (FWHM). The resulting average intensities were in the range of 10^{11}–10^{13} W/cm^2. The intensity was varied by suitably attenuating the laser beam using neutral density filters. A second harmonic probe beam (0·53 μm) was generated by splitting a fraction of the main laser beam and frequency by converting it into its harmonic using a type-1 phase matched KDP crystal. The probe pulse duration was shortened to 1·5 n sec to obtain a better temporal resolution. The schematic experimental layout is shown in figure 1(a). Shadowgrams were recorded on a polaroid 107 film with a 6 μm spatial resolution. A variable optical delay line in the

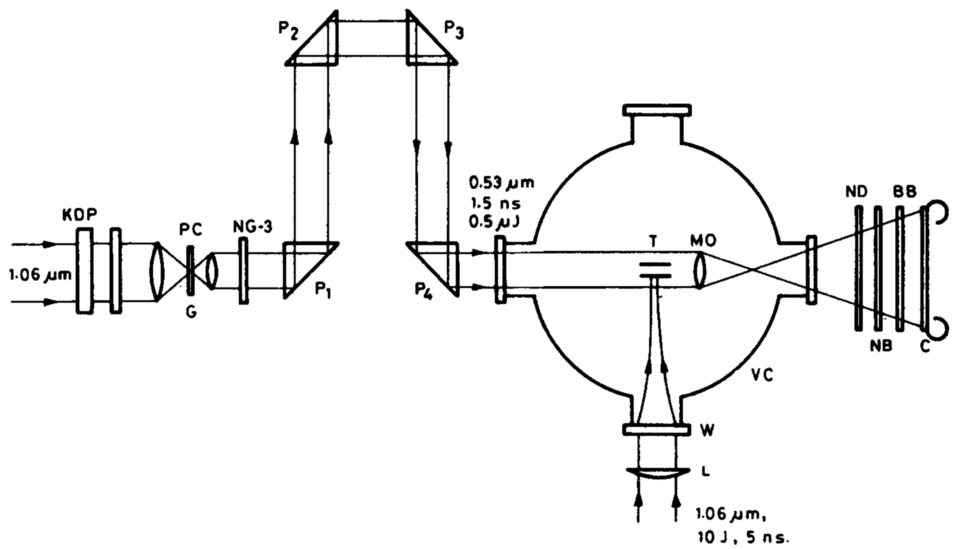


Figure 1a. Schematic of the experimental layout. T, Target foils; L, focusing lens for the main laser; MO, microscope objective for imaging the target; VC, vacuum chamber; W, window; KDP, KDP crystal for second harmonic generation; PC, probe pulse compression scheme using breakdown in a glass plate-G; NG-3, 1·06 μm cut-off filter; P_1, P_2, P_3, P_4 are folding prisms of the delay line; ND, neutral density filters; NB and BB, narrowband and broadband filters to transmit only 0·53 μm; C, polaroid camera.

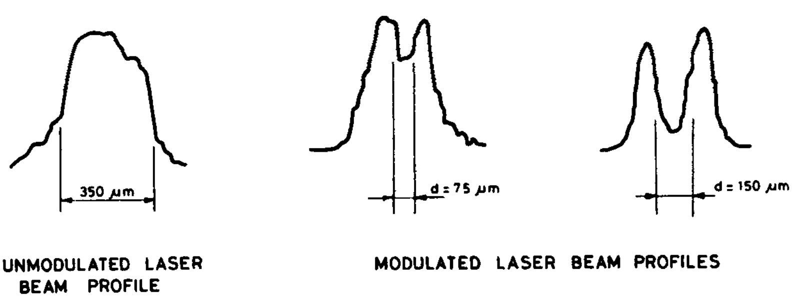


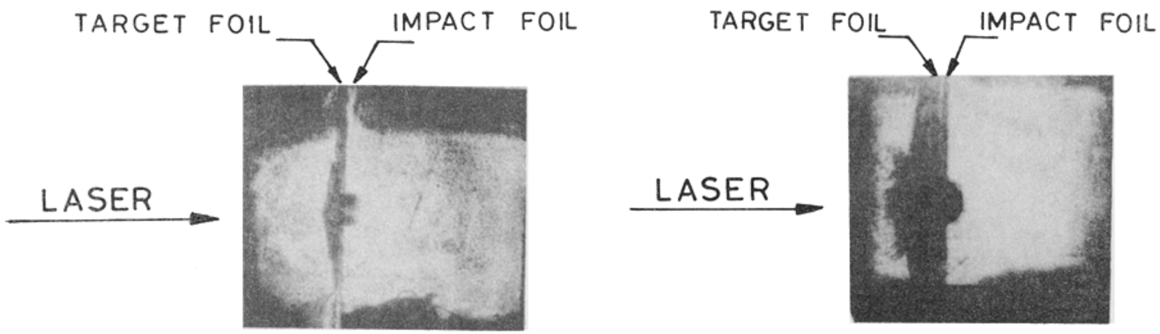
Figure 1b. Incident laser spatial intensity profiles.

path of the probe beam was introduced to record the shadowgrams of the accelerated foil at any desired instant of time with respect to the peak of the main laser pulse. The targets used in these experiments were 10 μm thick plastic foils with or without a 0·1 μm thick gold coating as an ablator.

To study the effect of beam non-uniformity on the stability of ablatively accelerated thin foil targets, the incident beam profile was spatially modulated by inserting opaque horizontal strips of different widths across the laser beam diameter which gave an intensity profile as shown in figure 1(b). The FWHM at the central intensity dip d was 75 μm and 150 μm in the experimental conditions chosen by us. Single thin foils have been shown to be less reliable for the study of target dynamics due to the rear heating of the foil and generation of a low density plasma (Grun 1982). This plasma refracts the visible probe beam and casts its shadow thus giving an exaggerated idea of motion of the dense foil. To overcome this problem, a double foil technique (Dhareshwar *et al* 1985) has been used in the experiments described here. A 2 μm thick aluminium foil placed at a close distance (50 μm) behind the target foil (10 μm plastic) served as an impact foil. This foil reacts to the impact of the dense part of the target foil only. The extent of smoothing in the target foil motion in this case is reflected in the impact foil motion. The modulation depth in the impact foil movement is measured and compared with the modulation depth in the incident beam intensity profile. Any error introduced due to the impact foil inertia is very small since its thickness is very small. The shock transit time (0·4 n sec) in this foil is also much less than the temporal resolution in these experiments. The shadowgrams obtained for a 10 μm plastic foil and a 10 μm plastic foil coated with 0·1 μm thick gold coating are shown in figure 2.

3. Results and discussion

The smoothing factor in the ablation or of the movement of the target foil can be defined by a factor $\Gamma = (Z_{max} - Z_{min})/(Z_{max} + Z_{min})$ where Z_{max} and Z_{min} are the extent of the impact foil motion at the points where the laser intensity is I_{max} and I_{min} respectively, at a given instant of time (as shown in figure 3). A complete smoothing therefore will show $\Gamma = 0$ whereas $\Gamma = 1$ corresponds to no smoothing. Since the smoothing is compared for the same value of d, but for the case where a coated and an uncoated foil is used, the absolute smoothing factor given by the ratio of velocity and pressure smoothing need not be considered. The absolute smoothing factor, Γ_{abs}, is given by γ_z/γ_a where $\gamma_z = (Z_{max} - Z_{min})/(Z_{max} + Z_{min})$ and $\gamma_a = (P_{max} - P_{min})/(P_{max} + P_{min})$. Also, γ_a can be determined by considering $\gamma_I = (I_{max} - I_{min})/(I_{max} + I_{min})$ and using the scaling (Grun 1983) $P \propto I_a^{0.78}$. This is so, because, γ_a varies only with the width d of the intensity modulation. The plot of Γ vs laser peak intensity is shown in figure 4. For $d = 75$ μm, it is seen that Γ falls from one to nearly zero even at an intensity of $0{\cdot}6 \times 10^{12}$ W/cm^2 when a 0·1 μm gold coating is given on the plastic foil. For $d = 150$ μm, there is an improvement in smoothing by 60 %. It is apparent that the lateral thermal transport in the conduction zone between the critical and ablation surface is not sufficient to smooth out the effect of laser beam non-uniformity in case of pure plastic targets. The only logical reason for the observed smoothing for gold-coated plastic target could be due to the copious x-rays produced during laser plasma interaction. These x-rays can penetrate deep into the conduction zone due to their short wavelength and being isotropic in nature, they heat the conduction zone to a higher



(a) (b)

Figure 2. Shadowgrams for unirradiated and irradiated foils at an incident laser intensity of 2×10^{12} W/cm^2. **(a)** 10 μm thick pure plastic foil. **(b)** 0·1 μm gold coated, 10 μm thick plastic foil. Gold coating faces the incident laser direction. Delay-3 n sec and 7 n sec for **(a)** and **(b)** respectively. Incident laser intensity–2×10^{12} W/cm^2.

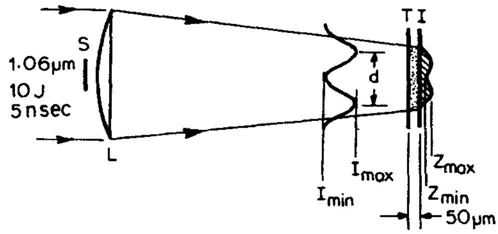


Figure 3. Schematic diagram to explain the meaning of I_{max}, I_{min}, Z_{max}, Z_{min}-L-focusing lens; T, target foil; I, impact foil; S, strip.

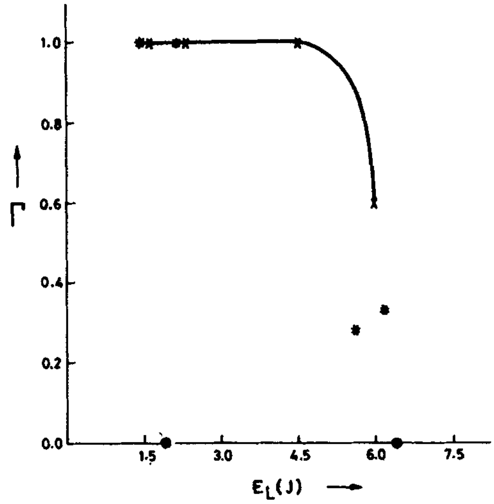


Figure 4. Variation of Γ with laser energy (E_L). * 10 μm plastic, $d = 75$ μm; × 10 μm plastic, $d = 150$ μm; ⊕ 10 μm plastic with 0·1 μm gold coating, $d = 75$ μm; ⋕ 10 μm plastic with 0·1 μm gold coating, $d = 150$ μm. Incident laser intensity $= 2 \times 10^{11}$ W/cm^2 per joule.

temperature uniformly, thus improving the thermal conductivity leading to a better lateral transport. Enhanced lateral transport in gold targets has also been shown in earlier results (Bocher *et al* 1984).

Further, a simple estimation has been done to obtain the classical thermal conduction length at a plasma temperature of about 100 eV (as in these experiments). The conduction length is about 10 μm (Dawson 1970). Obviously such a small conduction length cannot be expected to smooth out ablation profiles for $d = 75$ μm and 150 μm. We can therefore say that the smoothing occurred due to x-ray assisted lateral transport. Careful examination of the shadowgrams shows that the lateral dimension of the shadow of the front plasma is about 800 μm–1000 μm. However, the focal spot diameter in these experiments was only 350 μm. Therefore, one would have expected the diameter of the front plasma to be not more than about 400 μm.

The hydrodynamic efficiency which is the percentage fraction of the absorbed laser energy converted into the kinetic energy of the accelerated foil is another important parameter to be considered for efficient target implosion. The hydrodynamic efficiency for a coated and uncoated foil was determined by calculating the terminal velocity (V) of the target foil using a streak camera and using the equation, hydrodynamic efficiency = (kinetic energy of the accelerated foil)/(absorbed laser energy). Hydrodynamic efficiency for a gold-coated and an uncoated foil was 2·8 % and 3·6 % respectively, at a laser irradiance of 2×10^{12} W/cm^2. Thus we notice that the fall in hydrodynamic efficiency is insignificant.

In the experiments described in this paper, optical shadowgraphy technique has been used to record foil motion, though x-ray backlighting technique is considered to be the most suitable because of the fact that the motion of the ablation surface can be directly recorded. We have found that optical shadowgraphy technique can also be used to diagnose the foil hydrodynamics provided a double foil configuration is used. As mentioned earlier, this avoids errors in the determination of the target foil movement due to the presence of a cold, low density plasma on the rear side. In these experiments, the separation between the target and the impact foil was kept less than 50 μm so that the target foil makes an impact on the second foil before the 2D effects set into the motion of the target foil. The impact foil thickness is also kept small (2 μm) so that the transit time of the shock wave through this foil is very small. In that case the impact foil motion will not become apparently smoother due to its inertia. Under these conditions, the impact foil motion is truly representative of the motion of the accelerated target foil.

4. Conclusions

In these experiments, it has been observed that for 1·06 μm irradiation wavelength and intensity range of 10^{12}–10^{13} W/cm^2 a layer of a high Z ablator like gold on a low Z target foil like plastic smoothens out to a large extent the spatial non-uniformities in the target motion caused by a non-uniform incident laser beam. The smoothing is better than 80% and 60% for intensity modulation of 75 μm and 150 μm respectively at an average irradiance of 3×10^{12} W/cm^2. This observation can be explained on the basis of an enhanced lateral energy transport due to the x-rays generated from the high Z ablator. These x-rays increase the temperature of the region between the critical density and ablation surface which is not heated directly by the incident laser beam. Further, it has been observed that the difference in hydrodynamic efficiency for gold-coated plastic and pure plastic targets is less than 2%. This fact is encouraging, since, by suitably structuring the targets, one can think of a way to counteract the detrimental effects caused by a non-uniform spatial profile of the incident beam without causing a substantial loss in the hydrodynamic efficiency. Such layered targets are feasible and are being considered in the laser-driven implosion scheme (Nuckolls 1980) today. Although a detailed analysis is needed to discuss the quantitative nature of the problem and would be presented in future, the results presented here conclusively show that the effect of irradiation non-uniformity on target ablation can be successfully overcome by coating targets with a layer of a high Z ablator, like gold, without a significant fall in the hydrodynamic efficiency.

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