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Beam Nonuniformity Effects on Laser Ablatively Accelerated Targets

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We present results of a laser doppler shift technique which gives the velocity profiles of ablatively accelerated targets. Measurements of the effects of laser beam nonuniformity on the target acceleration are presented and interpreted in the context of laser pellet fusion.

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BEAM NONUNIFORMITY EFFECTS ON LASER ABLATIVELY ACCELERATED TARGETS

Laser pellet fusion involves imploding pellets through reaction to laser induced ablation of the pellet surface. The complicated problem of efficiently coupling the laser energy to the pellet and producing the proper conditions for a fusion burn have led in some cases to opposing requirements. Experiments and theory indicate that the most efficient coupling of laser energy to an imploding pellet should occur at the lower range of practical irradiances (10^{13} - 10^{14} W/cm^2).[1,2] This low irradiance requires pellet designs[3] where thin pellet walls (thickness ΔR) are accelerated over relatively long distances (R) towards an implosion at the center: ($R/\Delta R \gtrsim 10$). There are severe requirements on the uniformity of the pellet walls and on the ablation pressure ($\Delta P/P \lesssim 1\%$) for such designs if one is to achieve high pellet gains.[3,4] An important question is what is the relation between nonuniformities in the incident laser beam, $\Delta I/I$, and nonuniformities in the ablation pressure, $\Delta P/P$, for various perturbation wavelengths? As discussed later, lateral energy flow can smooth the effects of beam nonuniformities and relax the requirements on the laser.

Some of the problems of laser ablative acceleration of pellet walls are being addressed by a series of experiments at NRL wherein planar thin-foil targets are ablatively accelerated by a multi-nanosecond Nd-glass laser beam.[5,6] We will discuss the results of a novel doppler-shift diagnostic technique which gives time resolved velocity profiles of the accelerating target. This diagnostic has proven useful in exploring the laser beam requirements for uniform ablative acceleration.

Figure 1 shows the experimental arrangement. The 3-nsec FWHM main laser beam (1.05 μm) is focused onto a planar foil target. The rear

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target surface is illuminated at normal incidence by a 400-psec duration 0.527 μm optical probing beam and the reflected probe light is focused onto the entrance slit of a stigmatic spectrograph. By measuring the doppler shift ($\Delta\lambda = 2v\lambda/c$) of the probe light as a function of position across the accelerated target, one obtains the target velocity profile $v(x)$. Details on techniques for conducting these measurements are given elsewhere.[7]

Figure 2(a) gives the velocity profile obtained from the doppler shift measurements at a time near the peak of the main laser pulse for the case of a 9 μm thick carbon target and a peak laser irradiance of about 5×10^{12} W/cm^2. The measured incident laser profile across the target is given for comparison. Under these conditions, the doppler shifts indicate that a relatively uniform laser beam results in a target being relatively uniformly accelerated. Lateral energy flow apparently causes the accelerated target region to be somewhat larger than the incident laser profile.

Before considering other results, we shall briefly discuss whether the doppler shift technique accurately measures the motion of the target mass. There are a number of possibilities. The probe light may be reflected from the solid accelerated target surface or, if a plasma is present, it can be reflected at the critical layer for the probing wavelength ($n_e = 4 \times 10^{21}$ cm^{-3}) which corresponds to about 1% of solid density. For the former case, the doppler results clearly represent the target motion. The relatively thin targets employed should preclude significant shock phenomena because the transit time of a sound wave through the targets is shorter than the laser pulse rise time. For the second case, where a plasma is present, there are potential complications which will be addressed. For example the probe may be reflected from the critical layer of a plasma expanding outward at a higher velocity than the denser target material. In addition, plasma expanding through the reflecting layer can yield an additional blue shift due to a changing plasma density profile. For these effects to be significant, the rear surface of the target must be hot. Measurements of emission from the rear of the targets employed indicate peak temperatures of less than 10 eV which occur well after (a few nanoseconds) the measurements presented here.[8] At these low temperatures, the probe would be nearly totally absorbed after passing through only a few wavelengths of near critical density plasma.[9] The presence of significant reflection for the times and targets employed places an upper bound of approximately 1 μm on the plasma density scalelength. This scalelength is small compared to the target motion (>10 μm) during its acceleration. Therefore if the probe is reflecting from a critical layer, the plasma density scalelength is short enough for the measurements to reflect the actual target motion.

For our experimental conditions the doppler shift measurements should accurately give the velocity structure of the accelerated target and thus provide an indication of the corresponding ablation pressure profile.
We have used the doppler technique to investigate the effects of nonuniformities in the main laser beam on target acceleration. For the results presented in Figs. 2(b) and 2(c), the incident laser spatial profile was intentionally distorted by placing progressively wider strips of opaque material in the main laser beam at the lens. The measured laser profile at the target plane and the computed laser profile, assuming no amplitude or phase modulations in the undisturbed beam, are given for comparison. For the focused laser nonuniformities of the amplitude and scalelength shown, the nonuniformities are clearly imprinted on the accelerating target velocity profile.

Before interpreting these results, we will briefly discuss what to expect. Figure 3 illustrates the interaction of the laser with an ablatively accelerated target. The distance from the ablation layer (where the pressure is applied to the target) to the absorption (critical) layer is given by L. For the case where the scalelength of laser nonuniformities (D) is much shorter than this separation distance ($D \ll L$), one expects the lateral energy flow to smooth the effects of laser beam nonuniformity. In the opposite extreme ($D \gg L$) one expects the nonuniformities to be transmitted to the target ablation region. One dimensional theory[10] and experiments[11] indicate that the ablation pressure is a power function of laser intensity with $P \propto I^n$ where $n \approx 3/4$. Using this, one obtains for the case of long scalelength ($D \gg L$) laser intensity nonuniformities (ΔI):

$$\frac{P + \Delta P}{P} \approx \left(\frac{I + \Delta I}{I} \right)^{3/4} .$$

The ablation pressure nonuniformities will be reflected in the target acceleration and velocity (v) profiles provided the nonuniformity scalelength is larger than the target thickness. One obtains the relations $dv/dt \propto P$ and $\Delta v/v = \Delta P/P$, provided the ablated target mass is much smaller than the initial target mass, a condition satisfied for the experiments discussed here. Note that this simplified analysis does not consider the possible effects of Rayleigh-Taylor instability which can cause nonuniformities to grow even with a highly uniform laser and target combination. The classical Rayleigh-Taylor exponentiation time for the accelerations (5×10^{14} cm/sec^2) and nonuniformity scalelengths ($\gtrsim 100\,\mu m$) encountered in the experiments reported here is long enough (>2 nsec) to preclude it from being a dominating effect.

For the experimental conditions of Fig. 2, side-on shadowgraphy with the 527 nm probe indicates that the distance from ablation to critical layer is less than 150 μm ($L < 150\,\mu m$). Computations predict that the separation distance for the irradiances employed should be approximately 100 μm.[12] In Figs. 2(b) and 2(c), 4-to-1 and 6-to-1 beam nonuniformities over a scalelength of 100 μm yielded 1.6-to-1 and 2-to-1 velocity nonuniformities in the accelerated targets. In the absence of lateral transport, Eq. (1) predicts significantly larger velocity nonuniformities of 3-to-1 and 4-to-1 respectively. This indicates there is some, but far from complete smoothing of the effects of beam nonuniformity due to lateral energy flow. This is a result one would expect in this middle range $D \approx L$ regime. Similar results have been reported earlier using interferometry and shadowgraphy.[1] However the doppler shift technique has allowed greater sensitivity and more quantitative evaluations of the effects of beam nonuniformities.

Laser fusion implosions of the type discussed earlier require very symmetric implosions of material in order to obtain the required densities and temperatures. Our results indicate that, at a wavelength of 1.05 μ m, and an irradiance (5×10^{12} W/cm^2) near the lower bounds at which laser fusion implosions appear practical, nonuniformities in the incident laser beam with scalelengths greater than 100 μm result in nonuniformities of the ablatively accelerated mass. The implied laser beam uniformity requirements for illuminating a fusion pellet perhaps several millimeters in diameter are very severe. It is however likely that the separation between the absorption and ablation regions will be longer at higher irradiances due to the higher temperatures and increased ablation rates of material. This should cause increased smoothing of laser beam nonuniformities. At irradiances much above 10^{14} W/cm^2, it is expected that the benefits of increased smoothing must be balanced against well known problems, including poor absorption, preheat and plasma instabilities that can occur at high irradiances.[6] Further experiments at NRL will investigate the parametric dependencies of smoothing in the regime between 10^{13} and 10^{14} W/cm^2.

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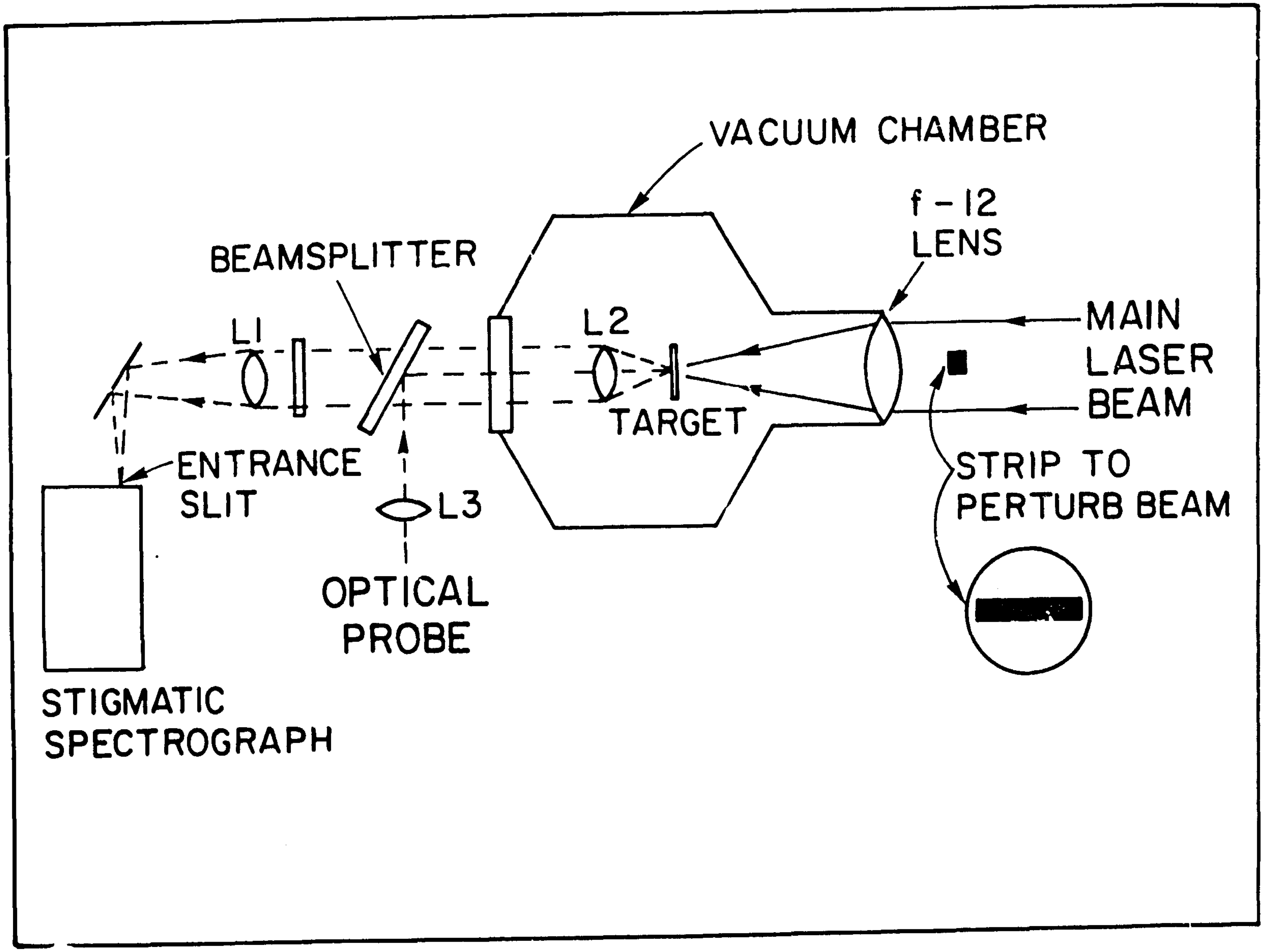

Fig. 1 — Experimental arrangement for determining the velocity profiles of ablatively accelerated targets from doppler shifts of reflected optical probe light. These measurements have a velocity resolution of 10^5 cm/sec and a spatial resolution of 20 μm. For some experiments, the main laser uniformity is perturbed by placing strips of opaque material in front of the focusing lens.

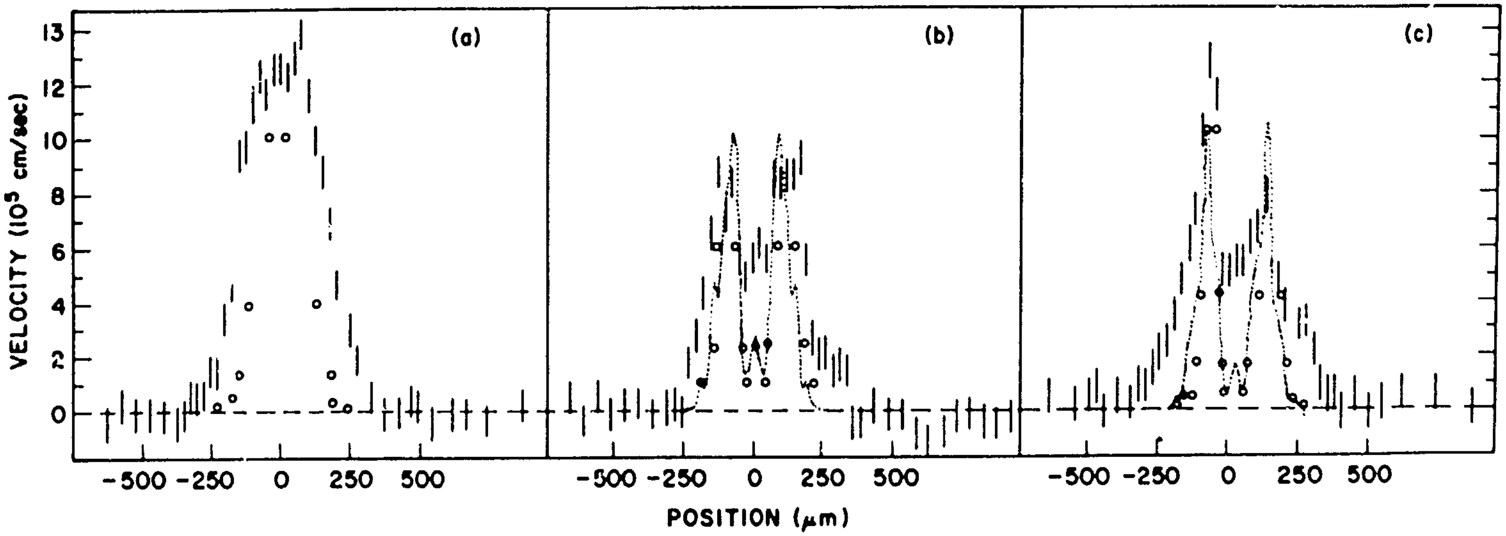

Fig. 2 — Doppler shift determined velocity profiles (vertical bars) for ablatively accelerated carbon targets at times near (within 300 psec) the peak of the main laser beam. The focused laser intensity profile measured at the target plane of an equivalent lens is given by the open circles, while the computed laser profile is given by the dotted lines. Case (a) corresponds to an unperturbed main laser beam, whereas in cases (b) and (c) 1 and 1.5 cm strips of opaque material were placed across the 10 cm diameter laser beam at the lens.

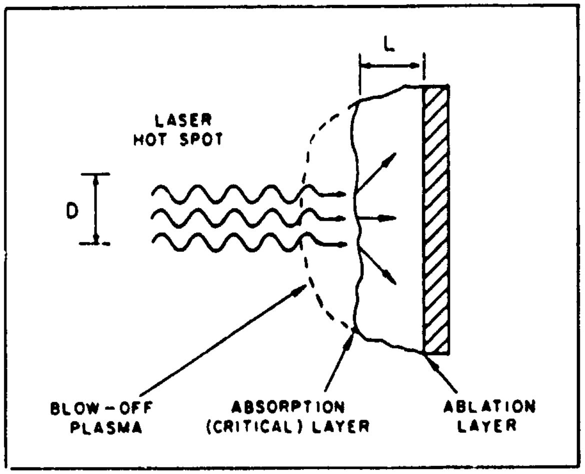

Fig. 3 — Illustration of the smoothing of a laser beam nonuniformity of scalelength D due to lateral energy flow in the blowoff plasma of an irradiated target.

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