Use of X-Ray Preheated Foam Layers to Reduce Beam Structure Imprint in Laser-Driven Targets

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A new direct-drive scheme is proposed, which substantially reduces initial laser-nonuniformity imprinting by surrounding conventional targets with a low-density foam jacket. The foam is ionized by a supersonic wave induced by a soft x-ray pulse prior to the arrival of the main optical drive. The variable-sized, supercritical foam plasma thus created acts to thermally smooth laser-drive structure. Hydrocode simulations are presented showing that the scheme is very effective at reducing target nonuniformities due to imprinting without significantly increasing target preheat and reducing hydrodynamic efficiency.

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It has long been recognized that high gain direct-drive laser fusion will require a combination of nearly uniform laser illumination and thermal smoothing in the target plasma to achieve the necessary uniformity in implosions. In the past few years much progress has been made towards improving laser illumination uniformity with the development of incoherent optical smoothing techniques such as induced spatial incoherence (ISI) [1] and smoothing by spectral dispersion (SSD) [2]. Thermal smoothing due to diffusive heat transport between the energy deposition and ablation regions in the target reduces further the effects of drive nonuniformities. Such smoothing improves as the ratio of the width of this conduction zone ($\simeq D_{AC}$, the ablation-to-critical surface separation) to the wavelength of the energy deposition perturbations λ_{pert} increases, leading to the common use of the ratio D_{AC}/λ_{pert} to characterize the degree of smoothing in a target. Under typical inertial confinement fusion (ICF) conditions and for steady-state ablation, $D_{AC}/\lambda_{pert} \gtrsim 1$ and thermal smoothing is expected to be sufficient for acceptable drive uniformities to be achieved [3]. However, there is a transient stage at the beginning of the drive pulse, starting when the laser is incident on the cold target surface, during which D_{AC} grows from zero to its steady-state value. During this stage, thermal smoothing is ineffective and the large drive nonuniformities—present even in ISI-smoothed beams on short time scales ($\ll$ pulse length)—imprint themselves onto the target surface generating a nonuniform shock [4]. Such structure seeds both the Richtmyer-Meshkov (RM) [5] and Rayleigh-Taylor (RT) [6] hydrodynamic instabilities, which amplify the nonuniformities during the implosion and result in reduced implosion convergence, reduced gain, and possibly even in complete implosion failure if the shell breaks up before sufficient compression is achieved.

To date, the most promising proposal for reducing laser imprinting (and subsequent target breakup by RT growth) involves using an x-ray prepulse to generate a uniform plasma cloud around the target by ablation of the shell before interacting with the main laser drive. This approach is known as indirect-direct drive (IDD). The x-ray prepulse ensures that D_{AC} is nonzero when the main laser pulse arrives, so that thermal smoothing occurs immediately and early time laser-structure imprinting is reduced. Indeed, both experiments [7] and simulations [4] show the scheme to be effective in this respect. However, major problems remain with IDD. First, the x-ray prepulse launches a shock into the target, causing fuel preheat. Second, it is difficult to adjust the density scale length, and therefore the smoothing parameter D_{AC}/λ_{pert}, of the "buffer" cloud. If this parameter is too small, unacceptable laser imprinting will occur. If it is too large, the hydrodynamic efficiency of the implosion may be impaired.

In this Letter, we propose and investigate a new scheme, through which laser-structure imprinting may be reduced by an adjustable amount and with minimal shock-induced fuel preheat, while retaining all the advantages of direct drive as in the IDD scheme described above. In principle, this is similar to IDD, involving the generation of a uniform plasma buffer cloud around the target before the arrival of the main laser pulse. However, the drawbacks of IDD are avoided by surrounding the conventional ICF capsule with a low-density foam "jacket" and inducing in this a supersonic heat wave with a low-intensity "flash" of x rays to produce the uniform plasma cloud prior to the arrival of the laser pulse. Recent experiments [8] show that x-ray pulses readily generated with gold converter foils [7,8] can induce such heat waves in foam targets on account of the low material density. Supersonic preforming of a material layer outside the shell (as opposed to direct ablative preforming of the shell in IDD) reduces shock preheating, since the preforming heat front in the foam reaches the shell before any hydrodynamic disturbance, including the shock wave. The degree of smoothing D_{AC}/λ_{pert} provided by this new scheme—henceforth referred to as foam-plasma-buffered

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direct drive (FDD)—can be varied by simply adjusting the foam jacket thickness and therefore the size of the plasma cloud. The optimal buffer thickness then depends on the prevailing scale length $\lambda_{\rm pert}$ of the drive nonuniformities in a given laser system.

We present here the results of 1D and 2D hydrodynamic code simulations of planar foils (representing a generic target or a segment of an ICF shell) driven with nonuniform laser illumination both in the conventional direct-drive manner and using the FDD drive proposed here. Quantitative comparisons are made of the levels of target nonuniformtiy, preheat, and hydrodynamic efficiency attained in either case. The results are extremely encouraging, showing an $\geq 10\times$ improvement in the target uniformity with FDD without reducing hydrodynamic efficiency when compared to conventional direct drive. The critical initial "start-up" stage is examined in detail, since it is shown that the density and temperature profiles of FDD targets rapidly converge to those of conventional direct drive thereafter. Any subsequent motion or implosion is thus expected to follow that of highly uniform direct drive and is not discussed further here.

The computations are performed with a two-stage procedure. First, the effect of the x-ray flash (150 ps duration, Planckian, average flux level: 5×10^{12} W cm^{-2}) on the composite FDD target is calculated using a multigroup radiation transport model [9] coupled to the 1D Lagrangian hydrodynamics code MEDUSA [10] (the test target considered here can be readily manufactured and consists of a foam layer: 50 μm thick, 30 mg cm^{-3}, overcoated onto a foil: 15 μm thick, 1.4 g cm^{-3}, both CHO ($C_{15}H_{20}O_6$, triacrylate), with both the preforming x-ray flash and subsequent laser drive incident on the foam side). These codes show excellent agreement with experimental observations of x-ray heated foams [8] under very similar conditions to those investigated here. The output mesh (density and temperature) of the preheated target is then mapped onto the 2D Eulerian mesh of the hydrocode POLLUX [11] using a simple interpolation procedure and assuming uniformity in the direction transverse to the laser. It is also assumed that the foam layer is a continuous plasma after preheating, since neither voids nor pore compaction are modeled. This is expected to be valid under the prevailing conditions ($T \sim 50$ eV, typical cell size $D_{\rm cell} \simeq 1$ μm) since the pore closure time scale $D_{\rm cell}/v_T \simeq 15$ ps ($\ll$ preheat time of 150 ps), where v_T is the ion thermal velocity. The code is then run with $\lambda_L = 0.53$ μm (green), spatially modulated (in the transverse direction) light interacting with the composite target. Mesh resolutions of at least ten zones per transverse laser modulation wavelength and 0.3 μm in the axial direction are specified in order to adequately resolve the ablation process (control simulations with higher resolution do not differ significantly).

The striking improvement in target uniformity achieved with FDD is immediately evident from Fig. 1, which shows density contour plots taken from simulations of conventional direct and FDD drive (both targets have the same initial mass). Identical spatial modulations with a wavelength of $\lambda_{\rm pert} = 20$ μm and peak-to-trough amplitude ratio 7:1 (standard deviation $\sigma_I = 0.53$) are imposed on the laser drive (laser pulse shape: 100 ps rise to maximum intensity $I = 2 \times 10^{14}$ W cm^{-2} and constant thereafter) in the simulations. Clearly, the conventionally driven target is severely distorted on the scale of the beam nonuniformities, whereas the FDD target is almost completely uniform. Very similar results are obtained for $\lambda_{\rm pert} = 10$ μm.

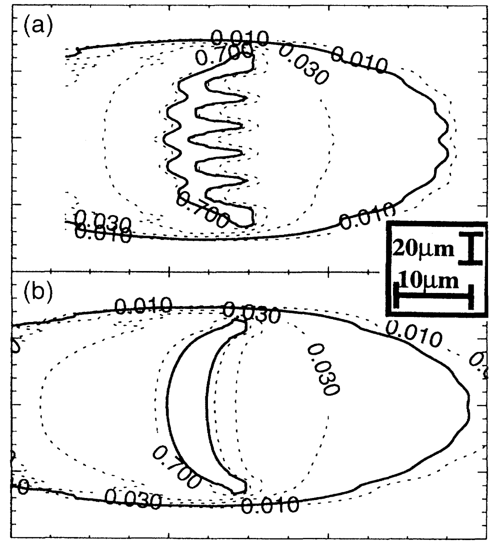

FIG. 1. Density contour plots taken from POLLUX simulations of targets driven with both conventional direct and FDD drive (drive incident from right, contours: labels in g cm^{-3}, solid lines at critical and solid densities). (a) Conventionally driven 15-μm-thick CHO foil. (b) FDD driven 13.9-μm-thick CHO foil with 50 μm foam buffer; other conditions as (a). The targets have moved $\simeq 30$ μm from their initial positions after 0.8 ns, when the frames are taken.

A quantitative comparison of the results for $\lambda_{\rm pert} = 10$ μm is made in Fig. 2 using the standard deviation of the target areal momentum density $\sigma_M(t)$ as a measure of the cumulative target nonuniformity [$\sigma_M(t)$ is defined as a standard integral from the rear of the target to the ablation surface over the central modulation wavelength]. Also plotted is the variation of $D_{\rm AC}$—the smoothing parameter—in both cases. Considering first the conventional direct-drive case (dotted lines), the critical early time transient stage (up to $t \simeq 0.25$ ns) is clearly visible with $D_{\rm AC}$ growing approximately linearly from zero to its steady-state value ($\simeq 25$ μm under the prevailing conditions). The plot of $\sigma_M(t)$, in turn, clearly shows that most of the laser-structure imprinting occurs during this early time stage. The target nonuniformity saturates at $t \simeq 0.3$ ns as thermal smoothing has become increasingly

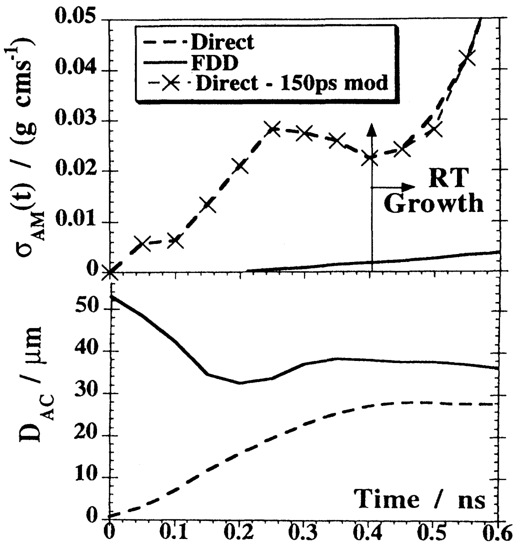

FIG. 2. Quantitative comparison of conventional direct drive and FDD scheme proposed here in terms of target momentum density standard deviation $\sigma_M(t)$ and smoothing parameter D_{AC} (conditions as in Fig. 1, except that $\lambda_{pert} = 10$ μm). The oscillatory variation of $\sigma_M(t)$ is due to ion-acoustic waves excited by the nonuniform ablation pressure. Also plotted is the $\sigma_M(t)$ variation when the laser modulation is turned off after 150 ps.

effective ($D_{AC}/\lambda_{pert} \simeq 1$ at approximately $t = 15$ ns). A similar simulation in which the beam modulation is turned off after $t = 0.15$ ns shows an almost identical $\sigma_M(t)$ variation (see Fig. 2), demonstrating that contributions from the laser intensity variations to the target nonuniformity in the period when satisfactory smoothing exists are relatively small for the parameter values considered here. Clearly, the time to saturation increases with λ_{pert}, but here the laser imprint is almost completely over when the shock breaks out at the rear of the target at $t = t_{SB} \simeq 0.4$ ns. RM instability growth is estimated to contribute less than 10% to the value of $\sigma_M(t)$ at shock breakout under our conditions [12].

In the FDD case in Fig. 2 (solid lines), on the other hand, D_{AC} is nonzero as the laser turns on, and is given approximately by the initial thickness of the foam jacket ($\simeq$50 μm, where the position of the ablation surface is taken to be at the foil edge facing the laser). Thus thermal smoothing is effective from the onset of the laser drive ($t = 0$). When the laser turns on in the POLLUX simulation for this case, the temperature at the front of the foam (side towards the laser) is $\simeq$50 and $\simeq$15 eV at the interface between the foam and the foil. The laser turn-on is chosen to coincide with the point at which the x-ray induced ionization front reaches the back of the foam and supersonic preforming of the buffer plasma is complete.

In the initial period of the laser drive up to $t \simeq 0.2$ ns, D_{AC} decreases as the laser drives a shock into and compresses the foam layer (see Fig. 2). At $t \simeq 0.2$ ns (when $D_{AC} \simeq 30$ μm) the shock passes from the compressed foam layer into the solid target with only a small reflected shock, since the density discontinuity at the interface is much less than the ratio of the cold foam and foil densities. After this point, the density and temperature profiles closely resemble those of an ordinary directly driven foil (a slightly lower-density gradient is observed with FDD). D_{AC} increases until nearly steady-state ablative flow is established at $t \simeq 0.6$ ns. After this point D_{AC} slowly falls as the foam layer is burned off and the flow becomes increasingly similar to that of the directly driven foil until at $t \simeq 1.5$ ns the flows are indistinguishable and D_{AC} is the same at $\simeq$25 μm in both cases. It is clear from the variation of $\sigma_M(t)$ observed in the FDD drive case that the effect of the foam layer is to reduce drastically the level of laser-imprinted structure. At shock breakout, the level of σ_M is $\simeq$10× less than in the conventionally driven target. At the same time, the total energy absorbed is slightly ($\simeq$3%) higher in the simulation of the FDD case.

After shock breakout (at t_{SB}), accelerated motion begins, when any ablation front nonuniformities are RT unstable and grow exponentially [6], potentially leading to shell breakup and thus implosion failure. This is clearly visible in the variation of $\sigma_M(t)$, which suddenly and rapidly grows after t_{SB}. The areal density growth rates determined from the simulations are in agreement with previous findings (see, for example, Ref. [13]).

Although the single spatial mode, 7:1 amplitude intensity nonuniformity case considered here serves to illustrate the essential physics of the FDD scheme, it is not, of course, representative of a real situation. Real beam structure is generally multimode with a lower overall modulation level ($\sigma_I \simeq 15\%$), although single-mode perturbations with levels even larger than those considered above (7:1) could occur in the case of a beam subject to filamentation. Simulations in which 20:1 amplitude, $\lambda_{pert} = 20$ μm intensity perturbations are specified show that FDD is effective even in the extreme case of drive filamentation. The perturbation level at t_{SB} is only 30% higher than the corresponding 7:1 FDD case considered in Fig. 1 (this nonlinear dependence on modulation amplitude is principally caused by increased lateral transport in the absorption region which serves to reduce the effective temperature perturbation). Simulations of less extreme conditions, in which realistic beam nonuniformity levels, spatial frequency spectra, and pulse shapes are specified show encouragingly low absolute levels of target nonuniformity with FDD. In the conventional coherent direct-drive case, a more realistic beam (six-mode: $\lambda_{pert} = 120$ μm$/m$, $m = 1, 2, \ldots, 6$, $\sigma_I = 14\%$ [14], intensity rising as $t^{3/2}$ reaching 2×10^{14} W cm^{-2} after 15 ns) produces a $\sigma_M = 42\%$ target nonuniformity after $\simeq$3 ns, when the target has been driven 30 μm (as in Fig. 1), sustaining $\simeq$3 e-folds of RT growth for the

$m = 6$ mode. This falls to $\sigma_M = 1.2\%$ when FDD drive is used under otherwise identical conditions, representing an improvement of 35×. Similarly low levels—1.6% and 2.2%—are observed at the same point when blue ($\lambda_L = 0.35$ μm) and UV KrF ($\lambda_L = 0.268$ μm) incident light are specified, respectively. When, additionally, the random fluctuations characteristic of ISI-type irradiation [1] with a laser coherence time of 2 ps are modeled, the nonuniformity falls to just $\sigma_M(t = 3 \text{ ns}) = 0.2\%$ with FDD for the case of green incident light. The results are thus extremely encouraging and it appears that the uniformity levels required for ICF (~1%–2%) may now be within reach if a combination of FDD and ISI-type drive is used.

A principal concern with the FDD scheme proposed here is that the foam "buffer-layer" may reduce the hydrodynamic efficiency of the system. This is because ablative flow has to be established initially through energy absorption in a region remote from the target surface and through an ensuing complex interaction in the foam. This aspect is examined in Fig. 3, using the displacement of the foil center-of-mass $d_{\text{c.m.}}$ as a measure of the hydrodynamic performance. Clearly, FDD drive does not significantly affect drive efficiency with the chosen foam parameter values, causing only a slight additional delay (≃50 ps) before the onset of accelerated motion. This behavior is confirmed by simulations made using the 1D Lagrangian code MEDUSA for conditions identical to those in the POLLUX simulations. The kinetic energy of the foil [defined as a standard integral in a manner similar to $\sigma_M(t)$] is actually 5% higher in the FDD driven foil after 1 ns. The 1D simulations provide a benchmark for the POLLUX results, since MEDUSA is known to accurately predict the experimentally measured hydrodynamic motion of foil targets [15]. The MEDUSA simulations also show that the rear surface foil temperature after shock breakout—an indication of the level of shock and x-ray preheat—is approximately the same in the FDD and conventionally driven targets at ≃5 eV, so that additional preheating due to FDD is small. Clearly it is important to minimize preheating due to the x-ray flash in FDD. This is achieved by minimizing the intensity and duration of the flash, subject to the constraints that the heat wave induced in the foam is supersonic and sufficiently long to preheat the foam layer completely.

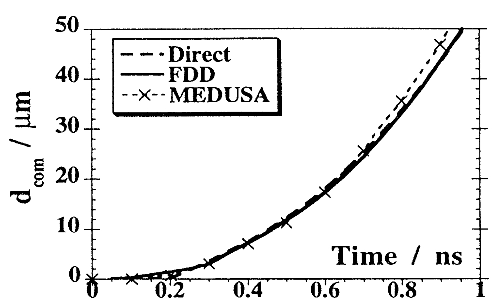

FIG. 3. Hydrodynamic performance comparison in terms of $d_{\text{c.m.}}$, the displacement of the foil center of mass. Virtually identical motion is observed with POLLUX for the case of a 50 μm foam layer considered in Figs. 1 and 2. This is confirmed by the MEDUSA simulation of the direct-drive case. All targets have the same initial mass.

In summary, a new technique is proposed to reduce early time laser-structure imprinting in direct-drive ICF and other applications. The scheme involves surrounding the target with a low-density foam jacket and generating from this a uniform plasma cloud with a supersonic ionization wave using a brief x-ray flash before interacting with the main laser drive. Supersonic preforming ensures that shocks and other hydrodynamic disturbances in the foam have only a minimal effect on the target shell. The foam plasma separates the energy deposition and ablation regions by a readily variable amount from the very onset of the pulse, so that thermal smoothing is effective throughout the drive. Simulations show that the scheme is highly effective at reducing target nonuniformities to below the levels observed in the conventional direct-drive case, without increasing target preheat or reducing the hydrodynamic efficiency. It appears that through the use of FDD and ISI-type drive, it may now be possible to achieve overall target uniformities close to those estimated to be required for high gain fusion.

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