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FOAM-BUFFERED LASER-MATTER INTERACTIONS

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FOAM-BUFFERED LASER-MATTER INTERACTIONS

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Abstract. Recent experiments indicate that low-density foam buffer layers can significantly mitigate the perturbing effects of beam non-uniformities in direct drive laser-matter interactions. Results of a computational study with a 2D ALE code are reported here. Typical targets consisted of 50 μm of 50 mg/cm^3 $\text{C}_{10}\text{H}_8\text{O}_4$ foam attached to a 10 μm foil and covered with 250 Å of gold. These targets were exposed to ~ 1.2 ns, flat topped, green light pulses at $\sim 1.4 \times 10^{14}$ W/cm^2 intensity, bearing 30 μm lateral perturbations. Without the buffer layers the foils were severely disrupted after 1 ns of laser illumination. Buffering could provide stability for more than 2 ns of full shell acceleration. Our study shows that the high thermal conductivity of the foam results in flattened shocks in the foam plasma, communicating a smoothed laser drive to the accelerated shells. Preheat from the gold hastens conversion of solid foam to the smoothing heated plasma.

INTRODUCTION

Direct drive inertial confinement fusion¹ (ICF) requires both smooth target surfaces and smooth illumination to avoid target breakup from Rayleigh Taylor² (RT) instabilities. The illumination is now regularly improved by both incoherent spatial interference³ (ISI), random phase plates⁴ (RPPs), and smoothing by spatial dispersion⁵ (SSD). In recent years optical beam smoothing techniques have been supplemented by the use of plastic foams to moderate the very earliest beam non-uniformities which might otherwise imprint before the optical techniques would have a time to improve the beam quality.

Okada et al.⁶ experimentally, and Emery et al.⁷ computationally were the first to suggest that the addition of a foam-like layer on the target surface might be used to mitigate laser illumination non-uniformities. Emery et al. examined the acceleration of solid DT with a uniform 50 μm DT "foam" layer of 80 mg/cm^3

density. They calculated mild mitigation of 40 - 50 μm scale perturbations on a KrF laser beam employing ISI. In 1995, Desselberger et al.⁸ first simulated the dynamics of a combined polymer-foam and planar foil target system. The foam was 50 μm long at 30 mg/cm^3 density and initially uniform. One dimensional (1D) calculations determined the mean foam plasma conditions following a 150 ps x-ray flash. Two dimensional (2D) calculations predicted a 35-fold reduction of RT growth in the foil for ~ 20 μm wavelength laser beam non-uniformities, with minimal concomitant degradation of the hydrodynamic efficiency.

Dunne et al.⁹ subsequently experimentally built and illuminated such foam-buffered targets at 50 mg/cm^3 densities, adding a 250 Å gold overcoat layer to complete the target package. The gold provided a source for x-ray ionization during the leading edge of the drive pulse. Compared to a directly driven foil target, the full target packages showed substantial mitigation of non-uniformities in the coherent laser beams used. Diagnostics measured greater RT growth when the gold preheat layer was removed, but less than with bare CH foils. Calculations predicted severe breakup of bare foils after 1 ns, but significant smoothing of 30 μm laser non-uniformities with the foam.

The ultimate purpose for foam-buffering is to facilitate high convergence DT implosions. Recent experimental campaigns have imploded foam-buffered cylindrical¹⁰ targets on VULCAN and TRIDENT, and spherical^{11,12} targets on NOVA. Improved symmetry from mitigation of the early imprint was apparent.

This paper examines important features of foam-buffered target dynamics. It presents results from LASNEX¹³ simulations of planar foils and foam in 1D and 2D, characterizes the dominant physics, and outlines significant parametric trends in foam buffered imprint mitigation.

CALCULATIONAL RESULTS AND DISCUSSION

Our simulations generally treated the target configuration of Fig. 1. Typical targets consisted of 10 μm of solid CH plastic at 1.1 g/cm^3 , covered by 200 to 30 μm of triacrylate ($\text{C}_{10}\text{H}_4\text{O}_8$) foam at 50 to 10 mg/cm^3 , and overcoated with a 250 Å preheat layer of gold. Such targets have been used in TRIDENT experiment in which 0.5 μm green light was delivered in a pulse which rose linearly over 100 ps to a peak intensity of order 1.4×10^{14} W/cm^2 . It was then flat-topped thereafter for 1 ns, and then linearly declining to zero over 100 ps. Only inverse-bremsstrahlung absorption was assumed.

FIGURE 1 (a) Schematic of a foam buffered target, (b) pulse shape for simulations.

The calculated plasma dynamics of these targets strongly depends on our choice for radiation transport modeling. A "3T" treatment¹⁴, characterizing the radiation as a single group diffusing with a Rosseland mean opacity -- as used in early ICF codes -- suggests that radiation from the gold penetrates rapidly to the CH foil, causing its explosion and the launching of a shock in the foam. This heads out rapidly towards the laser, to be greeted in the foam by an oppositely running shock from the drive. When, as an improvement, we employ a multi-group LTE radiation treatment with 73 groups, the foil again explodes, but in a "mushy" manner that launches no shock. The foil strongly "decompresses." Finally, when we go to a proper non-LTE treatment the foil mildly decompresses, and a strong shock is driven from the laser side into the foam until it hits the heated CH shell and accelerates it. The latter two calculated histories for a 50 μm 50 mg/cm³ foam layer are shown in Fig. 2.

FIGURE 2. The predicted r - t trajectories of the 1-D Lagrangian zone boundaries with (a) LTE and (b) non-LTE radiation diffusion modeling.

FIGURE 3. Relative intensity of time and space integrated spectra for a 250 Å gold outer layer under LTE and non-LTE, and with the gold replaced by 10 μm of CH.

The explosive expansion of the CH under LTE is associated with a flux of m-band radiation from the gold that is nearly 30 times greater at 2 to 3 keV than the corresponding intensity calculated with non-LTE. This is shown in Fig. 3, which presents the time-integrated radiation spectrum calculated to 100 ps. Furthermore, when 1 μm of solid plastic replaces the gold preheat layer, the m-band peaks disappear, and the smoothed intensity envelope drops in magnitude by another factor of ten. In non-LTE fewer electrons are elevated to higher energy states in the gold, and less energy is radiated. The spectrum is softer, absorbing closer to the surface of the CH foils. These effects can reduce the radiative decompression of the CH foils. Such a reduction is important, because it supports plans to use gold preheat layers on foam buffers outside of shells to be compressed to high density for direct drive ICF.

Experiments with a *detached* gold layer recently conducted by Afshar-rad et al.¹⁵ His team reported that the radiation from a 1500 Å gold layer illuminated by a 10^{15} W/cm², 0.5 μm laser launched a supersonic ionization wave in 50 mg/cm³ foam. This moved at 3.5×10^7 cm/s, raising the electron temperature to ~100 eV behind its front. We have calculated a similar configuration with LASNEX and see a similar front, accompanied by only a 10% concomitant rise in foam density, while the level of effective ionization Z_b (~1) rises substantially. This rapid increase in ionization is associated with the conversion by radiation of the solid foam into a plasma.

When the gold is attached to the foam, the rapid ionization front is still evident, but it is followed by a shock. Electrons are directly heated by the laser that drives this shock. In calculations for 1.4×10^{14} W/cm² illumination the ionization front moves at $\sim 1.2 \times 10^7$ cm/s with a modestly strong follow-on shock (~2.2/1 density rise) traveling at $\sim 6 \times 10^6$ cm/s. At 150 ps into the drive the electron temperature rises to 90 eV across the ionization front, and then up to 1.1 keV near the critical

surface. Ahead of the ionization front Z_b is at a default level of 10^{-2} . After it $Z_b \sim 2$, and beyond the shock $Z_b \sim 4$. The electron temperature profile exhibits a broad thermal front spanning the plasma from just ahead of the shock to the laser deposition front. Again, the precursor ionization front preconditions the foam, converting it from a solid to a plasma with $Z_b \sim 3$.

When the gold preheat layer is removed and the same laser drive falls directly on the foam, the chief new feature is that the electron temperature stays much lower (~ 20 eV) ahead of the shock, where $Z_b \sim 1.5$, and the shock becomes strong (with 4/1 density rise). Also, we see a much steeper thermal front just at the leading edge of the shock. However, except for the higher Z_b , it is not clear from such one-dimensional simulations why addition of the gold layer should improve the performance of foam-buffering, as seen in the experiments⁹.

We have conducted a number of parameter studies to help match the optimal foam characteristics to our targets. Without gold and at higher density, e.g. 100 mg/cm^3 , the steep rise in electron temperature occurs on the laser side of the pulse pushed by the drive. At lower density, say 25 mg/cm^3 , the electron thermal front moves inside to the leading edge of the pulse. Similarly, higher intensities, e.g. $5 \times 10^{14} \text{ W/cm}^2$, push the thermal front to the front of the density pulse, and a lower intensity moves it to the laser side. Our results are mildly sensitive to our choice of electron flux limiter¹⁶ f_e . A good match with foam experiments⁹ is obtained for $f_e = 0.05$. Figure 4 shows that a change from $f_e = 0.03$ to 0.08 results in about a 10% change in penetration distance at 200 ps. (The surface of the foam was initially at $50 \mu\text{m}$). For reference, we show that a reduction of the electron thermal conductivity with a multiplier $K_{em} = 10^{-4}$ reduces the shock front penetration speed by a factor of 2.5.

FIGURE 4. Densities and electron temperatures at 200 ps in uncoated foam for flux limiters near 0.05, or for electron thermal conductivity reduced by a multiplier $k_{em} = 10^{-4}$.

Generally, the speed of shock transit v_s across the foam scales as the foam density, $v_s \sim \rho^{-1/2}$. This corresponds to simple dependence on a sound speed which will increase as the laser deposits in targets with progressively lower foam density giving a drive electron temperature, $T_e \sim 1/\rho$. It also follows for a high Mach number shocks at constant driving pressure. Also, we find that for different intensities I , the shock speed obeys $v_s \sim I^{1/3}$, which derives from an energy flux $mnv_s^3 \sim I$. These findings have helped us to choose foam densities and lengths for our buffer experiments¹⁰⁻¹².

Experiments have shown that the additional old preheat layer helps buffered mitigation. To probe this effect computationally, we ran structured one dimensional (picket fence) simulations in which 50 μm of solid foam was initially represented as 50 solid density triacrylate 500 $\text{\AA}$ thick walls, separated by 50 micron size voids. The full foam buffer was modeled with 600 LASNEX zones. As illumination proceeded with the Fig. 1 pulse, the foam layers heated and eventually exploded, converting the foam to a uniform plasma. When the gold preheat layer was present, the conversion process was complete by 110 ps. Without it, there was still considerable structure present at this time, and conversion did not complete itself until ~ 140 ps. In 1D the general plasma conditions of density, ionization and temperature after conversion were much like those prevailing when a uniform plasma was simulated from the outset. However, for higher dimensional smoothing the gold preheated buffer plasma was uniform 30% sooner.

We have also used structured foam simulations to investigate low density foams at 0.35 μm . Experiments at Limeil¹⁷ have shown effective 3ω mitigation with bare 10 mg/cm^3 foams. LASNEX predicts that the critical density $8.9 \times 10^{21} \text{ e}^-/\text{cm}^3$ exceeds the fully ionized uniform foam density. So in uniform plasma none of the shock structures of Fig. 4 are established. However, simulations of the initial *structured* foam show that each solid layer successively presents a critical surface to the laser, permitting a shock and standoff distance that can aid smoothing.

We must go to, at least, two dimensions to see any actual smoothing. Initially, we configured LASNEX with a fixed Eulerian mesh for this purpose. Figure 5 shows the evolution of CH shells exposed to a mean $1.4 \times 10^{14} \text{ W}/\text{cm}^2$ pulse with the Fig. 1. time history. At first, non-LTE with 73 radiation groups was employed. We introduced a strong (60%) radial perturbation of the form $I = I_0 \sin^2(\pi r/\lambda_d)$. The wavelength λ_d was set to 30 μm , corresponding to disturbances arising in our TRIDENT laser experiments. With axial symmetry the actual disturbances are rings. In each Fig. 5 frame the foil density contours at $t = 0, 800 \text{ ps}$, and 1.3 ns have been overlaid. The contours are evenly spaced between 1.4 and 0.1 g/cm^3 . In frame (a) [no foam] we see four main density maxima at 800 ps, and considerable radial non-uniformity by 1.3 ns. In frame (b) [CH + foam- (but

no Au layer)] we see substantially smoother profiles. This is quantified in (c), which plots the radial density profiles out along the density peaks of the foils.

FIGURE 5. Contours of the evolving 10 μm CH shells: (a) without and (b) with a 50 μm 50 mg/cm^3 foam buffer. (c) Radial density cuts along the crest of the shells at 812 ps.

In subsequent calculations we found, first, that LTE gave the same result (to be expected with CH), and, then, that simple 3T also showed smoothing. In fact, smoothing was evident in the absence of any radiation transport calculation. It appears, instead, to depend on strong electron conduction in the foams.

To evaluate this and other 2D parametric dependencies, we found that to direct Eulerian approach was computationally excessive, e.g. 500 CRAY-YMP hours for each of the non-LTE Fig. 5 runs. Consequently, we adopted a simpler Euler-Lagrange approach. We configured the code to perform Lagrangian flow axially, but Eulerian hydrodynamics in the radial direction. This was to avoid the expense of fine axial Eulerian zones, as well as the substantial radial mesh tangling introduced by our large perturbations. We also focussed on just a single radial wavelength, instead of 5. With these changes 20 hours sufficed to complete a run.

One calculational subtlety encountered in all our computations was the need for a very thin light shield on the surface of our foam. This was partly an artifact of LASNEX, which does not contain models for either light propagation in insulators or breakdown. We used about 0.5 μm of solid CH, modeled -- only in so far as the ionization was concerned -- with an effective electron temperature of 100 eV. This allowed us to have a low initial ionization level for room temperature conditions in the foam, while still avoid early time light penetration though the foam to the CH surface. (A gold or aluminum preheat layer provides such shielding, as a convenient side effect.) This replicated opaque foam, as in current experiments. Without such a layer a few sporadic light rays were found to deposit directly on the CH shells during the first 5-10 ps of our pulse, with a subsequent highly disruptive consequence, as shown for 700 ps in Fig. 6.

FIGURE 6. Early penetration (at ~ 5 ps) of light: (a) through "transparent" foam, leading to (b) late time (700 ps) disruption of the foil. Only a $30 \mu\text{m}$ radial strip has been modeled.

A large number of 2D runs were made to characterize conditions favoring stability. We looked at either the gross structural integrity of the accelerated shells, as for Fig. 6(b), or recorded lateral disturbance growth, as measured by the parameter $m_l = (\int \rho(t) dz - \int \rho(t=0) dz) / \int \rho(t=0) dz|_{\text{max-radially}}$. With perfect stability the integrated $\rho \Delta z$ is a constant. Here, m_l measures deviations from constancy due to instability.

Earlier, we indicated that a high level of electron thermal conduction is crucial to successful mitigation. Figure 7 collects results for a series of typical runs for $1.4 \times 10^{14} \text{ W/cm}^2$ illumination, the Fig. 1 (b) pulse, and a 60% disturbance of $30 \mu\text{m}$ radial dimension.

FIGURE 7. (a) Instability growth rate m_l for electron thermal conductivity multipliers $K_{em} = 1, 10$ and 100 . (b) Corresponding density and temperature profiles at 450 ps, and (c) the associated fluid velocities.

We see from Fig.7 (b) that the thermal wave and shock penetrate more deeply by 450 ps, as the thermal conductivity is increased. Also, from frames (b) and (c) we see that with higher K_{em} the velocity at the ablation surface is higher, which is also qualitatively consistent with increased stability according to the Takabe formula¹⁸.

With additional simulation studies we explored the effectiveness of different foam thicknesses L_f versus disturbance wavelength λ_d . We examined the effects of 60% light perturbations. At $1.4 \times 10^{14} \text{ W/cm}^2$ it took ~ 280 ps for the shock to cross the 50 mg/cm^3 foam, and correspondingly, ~ 110 ps to cross $20 \text{ }\mu\text{m}$, and 1.1 ns to cross $200 \text{ }\mu\text{m}$. We looked at 10 to $300 \text{ }\mu\text{m}$ perturbations, and 20 to $400 \text{ }\mu\text{m}$ thick foams. Generally, when the foam was thicker than λ_d , a flat shock arrived at the CH shell, and it was subsequently accelerated with "stability" for at least 3 foam transit times. Here, "stability" was characterized as less than 10% peak to valley radial density variations in the shell.

Similarly, we varied the $0.5 \text{ }\mu\text{m}$ laser intensity from $I = 3.2 \times 10^{12}$ to $1.6 \times 10^{15} \text{ W/cm}^2$, with our standard $50 \text{ }\mu\text{m}$, 50 mg/cm^3 foam. We recorded a stability time τ_s , after which $\Delta\rho/\rho > 0.3$ perturbations appeared. At the lowest intensity this was only 750 ps, while at $1.4 \times 10^{14} \text{ W/cm}^2$ it was 2.5 ns, and at the highest intensity it was 5.5 ns -- implying a dependence of roughly $\tau_s \sim I^{0.32}$.

We also observed some decrease in foam smoothing ability, as the laser wavelength was decreased. Again, at $1.4 \times 10^{14} \text{ W/cm}^2$, but for 3ω light, the stability time dropped to 2.0 ns. For 4ω it was only 700 ps. Increased intensity can be used to lengthen τ_s at these shorter wavelengths, however.

CONCLUSIONS

We have outlined results from a comprehensive computer study of foam-buffered laser-matter interactions. Buffering is used to mitigate the very earliest laser beam non-uniformities, present before optical smoothing techniques can take effect. Generally, we have found that electron conduction dominates the smoothing. One must use an opaque foam, to guard against very early deposition before the onset of substantial ionization. For stability the foam thickness should exceed the wavelength of the perturbations to be smoothed. With $50 \text{ }\mu\text{m}$ of 50 mg/cm^3 foam (our standard choice) the 2ω , flat-topped pulse drive intensity should exceed $5 \times 10^{13} \text{ W/cm}^2$ for 2 ns of shell stability. Also, to assure the presence of a critical surface, one should keep the foam density above 10 mg/cm^3 . A thin gold pre-heat layer over the foam appears to help by hastening the conversion of the solid

foam to a plasma. The use of the gold should be sparing, however, to minimize radiative decompression of the underlying target.

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