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Performance of indirectly driven capsule implosions on NIF using adiabat-shaping

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Abstract. A series of indirectly driven capsule implosions has been performed on the National Ignition Facility to assess the relative contributions of ablation-front instability growth vs. fuel compression on implosion performance. Laser pulse shapes for both low and high-foot pulses were modified to vary ablation-front growth & fuel adiabat, separately and controllably. Two principal conclusions are drawn from this study: 1) It is shown that an increase in laser picket energy reduces ablation-front instability growth in low-foot implosions resulting in a substantial (3-10X) increase in neutron yield with no loss of fuel compression. 2.) It is shown that a decrease in laser trough power reduces the fuel adiabat in high-foot implosions results in a significant (36%) increase in fuel compression together with no reduction in neutron yield. These results taken collectively bridge the space between the higher compression low-foot results and the higher yield high-foot results.

1. Introduction

Inertial confinement fusion (ICF) implosions using indirect-drive are being conducted on the National Ignition Facility (NIF). In the indirect-drive technique, a precisely tailored sequence of laser pulses is used to compress a cryogenic layer of deuterium-tritium (DT) fuel to the high temperature plasma conditions required to initiate DT fusion reactions in the central hot spot core. Details of the driving laser pulse shapes are important for maintaining a low fuel adiabat [1] and also have been demonstrated to strongly influence the stability of perturbations growing on the ablation front [2-6]. Initial experiments conducted during the National Ignition Campaign [7] used a relatively low power and energy (15TW/15kJ) initial picket pulse (0-2 ns) followed by a low power (1 TW) trough (2-8 ns). These "low-foot" (LF) implosions were successful in achieving a high total (including ablator and fuel) areal density (ρR_{max} = 1.3 g/cm^2), but the measured neutron yield was significantly lower than expectations. This reduced yield was attributed to poor ablation-front stability. Subsequent "high-foot" (HF) implosions [8] using an increased picket (38TW/39kJ) and increased trough power (4TW) resulted in a 10X increase in neutron yield, though at the expense of reduced fuel compression. The adiabat-shaping campaign was conducted to test the performance of pulse shapes designed to achieved the best of the LF and HF implosions, i.e. both good fuel compression and good ablation-front stability.

2. Quantifying the fuel adiabat

As was shown in Clark [9], modifications to the "foot" of the laser pulse can have a significant impact. An increase in the picket power was found to significantly improve ablation-front stability, while a decrease in the trough power was shown to decrease the fuel adiabat. Figure 1(a) shows the specific changes that were made to the foot of both the LF and HF laser pulses in this study. The standard low-foot (black) and high-foot (red) pulses are shown with dashed lines. The adiabat-shaped (AS) versions of the low-foot (blue) and high-foot (green, orange) are shown with solid lines. The two AS HF pulses (AS HF #1 green, AS HF #2 orange) are nominally identical with the exception that the 2nd and 3rd pulses (not shown here) for AS HF #2 were advanced in time by 700 ps. This was done to achieve proper shock merger timing for the 20 μm thinner ablator used in AS HF #2.

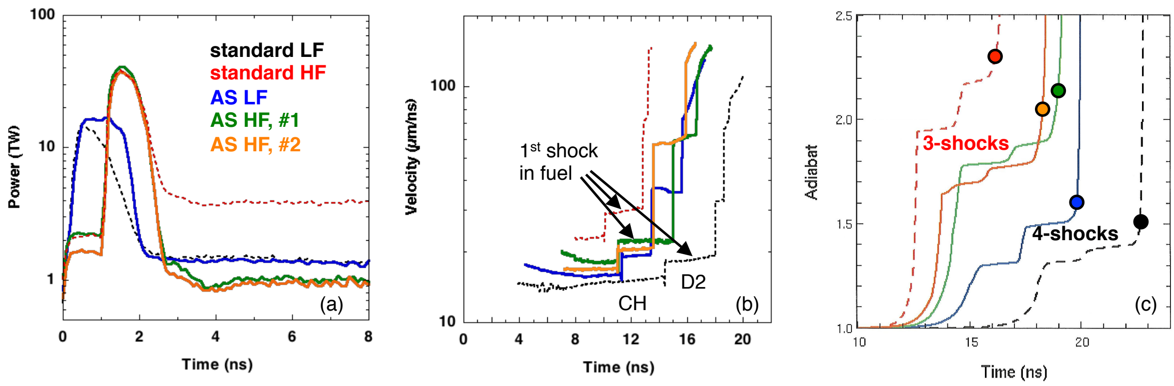

Figure 1. (a) Foot laser power histories for the five shots considered in this study. The standard LF (black) and HF (red) pulses are shown with dashed lines. The adiabat-shaped versions of the LF (blue) and HF (green, orange) are shown with solid lines. (b) Measured VISAR shock velocity histories for all five pulses with the same colors as the laser pulses of (a). (c) Plot of simulated fuel adiabat time history for all five pulses. The symbols indicate the adiabat at the time of peak fuel velocity.

The picket energy of the AS LF pulse was increased from 15 to 23 kJ by extending the duration of the picket by ~400 ps. In contrast, no change was made to the picket of the AS HF pulses. The trough power of the AS HF pulses was decreased from 4.0 to 1.0 TW. The timing of subsequent higher-power portions of all AS pulses (not shown here) was advanced to achieve proper shock merger timing. This results in all three AS pulses being of similar duration (~16-17 ns), a value that is intermediate between the standard LF and HF pulses. Note that the total changes in pulse energy that have been made are very small, with a total energy difference less than 0.5% from the standard LF and HF companion pulses.

The corresponding shock velocity histories measured by VISAR [10] for each of these pulses are shown in Fig. 1(b). The entire shock velocity history for all AS pulses falls between those of the standard HF and LF. The velocity of the 1st shock is important, as it adds most of the entropy to the fuel. The first shock velocity for the AS LF (blue, 19.0 μm/ns) is very comparable to that of the standard LF (black, 18.5 μm/ns) as intended, since no change was made to the trough of the laser pulse, which controls the 1st shock velocity [1]. The average first shock velocity for the two AS HF pulses are a little higher than the two LF pulses at 22.2 (green) and 20.45 μm/ns (orange) for AS HF #1 and #2, respectively. Both are substantially lower than the standard HF pulse, though, which has a first shock velocity of 29.7 μm/ns (red).

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One-dimensional simulations using the radiation-hydrodynamics code HYDRA [11], tuned to precisely match the VISAR-measured velocity histories of Figure 1(b), can be used to extract the mass averaged entropy of the fuel layer, from which the adiabat can be obtained. The temporal history of the simulated adiabat is plotted in Figure 1(c). The various steps seen in these adiabat time histories correspond to the entropy added during the traversal of the sequential shocks. The circle symbols indicate the value of the fuel adiabat at the time of peak fuel velocity. The adiabat values are 2.3 (HF, red), 2.1 (AS HF #1, green), 2.0 (AS HF #2, orange), 1.6 (AS LF), and 1.5 (LF, black). Note that a significant difference remains in the adiabats of the LF and HF cases. This is simply due to the difference in the number of driving pulses (3 for all HF-based pulses and 4 for all LF-based pulses), and therefore the number of shocks and corresponding pressure jumps seen in the fuel.

3. Quantifying the ablation-front stability

Having discussed the effect of these small changes to the foot of the laser pulse on the fuel adiabat, we now turn our attention to the corresponding effect of these same modifications on ablation-front stability. Figure 2(a) shows a schematic of the experimental geometry that is used on NIF in the Hydro-Growth Radiography (HGR) target platform. This geometry and the initial experiments are described in detail in Refs. [2,3]. A standard NIF hohlraum and capsule are used. A Au diagnostic cone, similar to that used in keyhole experiments [12], is used to provide a diagnostic line-of-sight for the 4.3 keV backlighter x rays, which are produced by interaction of two quads incident on a Vanadium foil located outside the hohlraum. The capsule is precisely machined with sinusoidal perturbations of very small initial amplitude on the outer surface within the field-of-view of the diagnostic x-ray framing camera. A comparison of the resulting optical depth modulations in the x-ray images at a capsule radius of ~ 650 μm (convergence of ~2X) is shown in Figure 2(b) for all four pulses. The agreement between simulated and measured growth is very good. Growth in the HF implosions is measured to be ~4X less than that of the LF, and both AS pulses show similar growth to that of the HF pulse. Further comparison of data with simulations is given in [13].

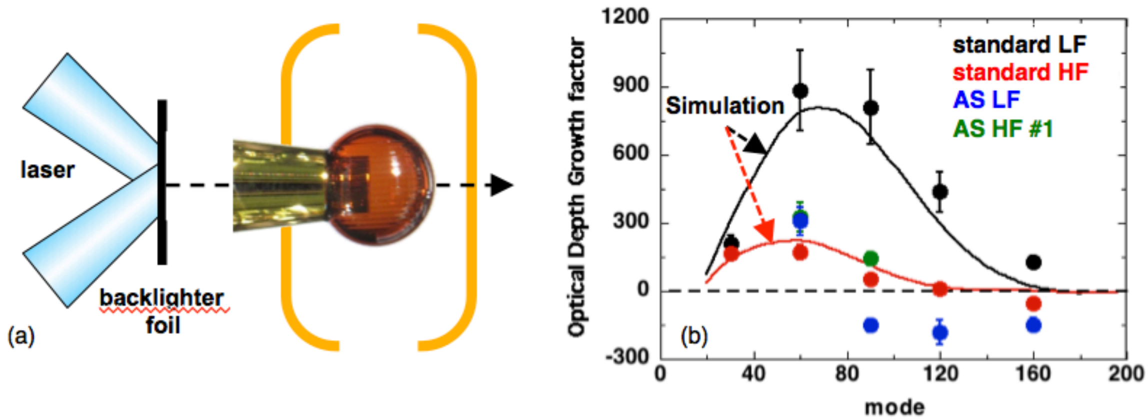

Figure 2. (a) Schematic of the Hydro-Growth Radiography (HGR) experimental platform. (b) Measured optical depth growth factor dispersion curves for all four pulses.

4. Effect of adiabat-shaping on implosion performance

In this Section, the performance of the three adiabat-shaped implosions of Figure 1 is discussed. We begin with the AS LF pulse (blue) of Figure 1(a). To summarize earlier observations, this pulse showed a very similar adiabat in Figure 1(c) but significantly improved stability in comparison to the standard LF pulse in Figure 2(b). Figure 3 shows the parameter space of neutron yield vs. DSR for all NIF shots. Shot N141123 (magenta) was an AS LF shot with a total laser energy of 1.6 MJ and a peak laser power of 336 TW. It is compared in Figure 3 with 5 companion shots from the NIC database that had very similar laser power and energy. Complete experimental details of this shot are given in Casey [14]. This shot exhibited a 3-10X increase in neutron yield with no loss of compression (blue vertical arrow) as compared to its companion shots. These results strongly indicate that ablation-front instability growth was indeed a major factor in degrading the yield of NIC LF implosions.

We now turn to the performance of the two AS HF pulses of Fig. 1(a). To review the previous observations, these pulses showed a moderately reduced adiabat in Figure 1(c) and similar stability to the standard HF in Figure 2(b). Results for the lower power shot N150115 (pulse AS HF #1) showed a significant increase in DSR (36%) and a modest (10%) increase in yield over similar power high-foot companion shot N150610. This is a clear consequence of the decreased adiabat of Figure 1(c) allowing increased fuel compression.

Increasing laser power in the AS HF pulse, however, resulted in a more modest increase in DSR. In shot N150416, a 20 μm thinner capsule was used, peak laser power was increased from 328 to 388 TW, and total laser energy was increased from 1.58 to 1.74 MJ. The foot of the pulse remained the same, however, and the adiabat was expected from Figure 1(c) to decrease slightly from the lower power AS HF shot N150115. This should correspond to increased fuel ρR and a higher measured DSR. As Figure 3 shows, however, the DSR increased over companion high-foot shots N140520, N150121, and N150409 by only 14%, as opposed to the 36% increase seen at lower power. The DSR on shot N150416 (4.65%) actually decreased relative to that of shot N15015 (5.04%), contrary to expectations from the measured adiabats of Figure 1(c). Total neutron yield (including the down-scattered component) was 8.41e15, very comparable to similar high-foot shots N140520 (8.98e15), N150121 (7.33e15), and N150409 (8.07e15). This decrease in fuel compression with increasing laser power strongly suggests that additional physics is playing a role in offsetting the increased fuel compressibility. The possible role of increased electron preheat is discussed in Ref. [13].

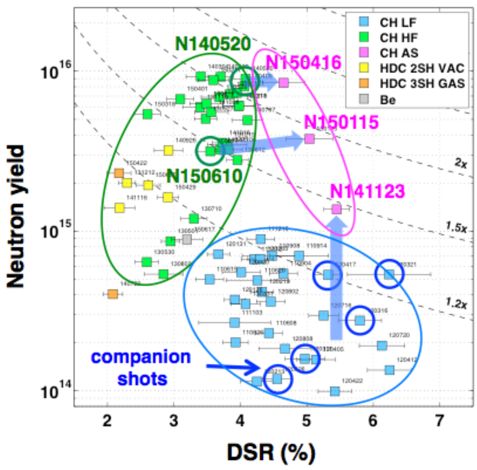

Figure 3. Plot of measured neutron yield vs. DSR. Low-foot shots are shown in blue, high-foot shots in green, and adiabat-shaped shots in magenta. Similar power and energy companion shots are circled.

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