# Differential ablator-fuel adiabat tuning in indirect-drive implosions

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Phys. Rev. E **91**, 031101 — Published 9 March 2015

DOI: 10.1103/PhysRevE.91.031101

# Differential ablator-fuel adiabat tuning in indirect-drive implosions

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(Dated: February 12, 2015)

We propose a design adjustment to the High Foot laser pulse [T. R. Dittrich *et al.*, Phys. Rev. Lett. **112**, 055002 (2014)] that is predicted to lower the fuel adiabat, increase compression and neutron production, but maintain similar ablation front growth. This is accomplished by lowering the laser power between the first and second pulses (the "trough"), so that the first shock remains strong initially but decays as it transits the ablator and enters the capsule fuel, in a process similar to direct drive "adiabat shaping" [S. E. Bodner *et al.*, Phys. Plasmas **7**, 2298 (2000)]. Integrated hohlraum simulations show that hohlraum cooling is sufficient to launch decaying shocks with adequate symmetry control, suggesting that adiabat shaping may be possible with indirect drive implosions. Initial experiments show the efficacy of this technique.

Ignition, the grand challenge of inertial confinement fusion (ICF), requires the compression and heating of cryogenic deuterium-tritium (DT) fuel to thermonuclear conditions [1]. In the laser indirect drive approach to ICF being pursued at the National Ignition Facility (NIF) [2], the DT is layered inside a millimeter-sized spherical capsule of moderate-Z material (such as plastic [3], high-density carbon [4] or beryllium [5]) that rests in the center of a centimeter-sized cylindrical high-Z cavity, or hohlraum. Discrete laser beams are fired through laser entrance holes (LEHs) on the axial ends of the hohlraum and strike the inner hohlraum wall. The hohlraum heats and emits x-rays, which ablate the surface of the capsule, causing it to implode and compress. The ultimate goal is for the center of the capsule to reach fusion relevant temperatures and densities and ignite a thermonuclear burn wave, which propagates throughout the DT fuel, producing more energy than the laser delivers to the hohlraum.

The efficiency of this process depends on the entropy of the DT fuel. Specifically, the lower the entropy of the fuel, the more it can compress. The fuel entropy can be characterized by the "adiabat" ($\alpha$) of the implosion - the ratio of the fuel pressure to the Fermi-degenerate pressure [6]. Because the ignition condition scales strongly with $\alpha$ (as an example, for an idealized isobaric stagnated state, the minimum energy required for ignition scales as $\alpha^3$ [7]), one of the great accomplishments of the National Ignition Campaign (NIC) was generating implosions with low adiabats, $\alpha \simeq 1.5$. By keeping $\alpha$ low, the NIC point design was able to achieve ignition-relevant fuel densities [8, 9].

However, the NIC point design did not achieve ignition [10]. While this result may be due to several compounding deficiencies, the lowest performing NIC shots (in terms of total fusion neutron production) saw evidence of capsule material polluting the hotspot, at times an order of magnitude above ignition tolerances [11, 12]. A leading hypothesis for the cause of this is hydrodynamic shell-breakup. In particular, Rayleigh-Taylor (RT) [13, 14], Richtmyer-Meshkov (RM) [15, 16], and Kelvin-Helmholtz (KH) [17, 18] fluid instabilities can harm ICF implosions [19–21]. Shocks launched during the early part of an implosion cause the ablative RM growth of surface imperfections, which can seed ablative RT growth during the main capsule compression. Growth depends on conditions set at the ablation surface, with the RM and RT growth largely set by the initial shock and main drive conditions, respectively [22]. The ablative RM growth factor (the ratio of a perturbation amplitude relative to its initial amplitude) of mode $k$ is oscillatory, with an amplitude proportional to $c_s/\sqrt{v_a v_b}$ and a frequency $\omega = k\sqrt{v_a v_b}$, where $v_a$ and $v_b$ are the ablation and blow-off plasma velocities and $c_s$ is the post-shock sound speed [21]. Ablative RT growth is much larger, however. It is exponential, with a growth rate of the form $\gamma_{\rm RT} \simeq \alpha\sqrt{kg/(1+kL_m)} - \beta v_a k$ [23]. Here, $\alpha$ and $\beta$ are constants (of order unity) that depend on the Froude number ($Fr = v_a^2/gL_0$) and thermal conduction exponent $\nu$ at the ablation front, $g$ is the acceleration, and $L_m$ is the minimum ablation front scale length, which is related to the ablation front width $L_0 = L_m\nu^\nu/(\nu+1)^{\nu+1}$. Spherical convergence Bell-Plesset (BP) [24] growth serves as an additional amplification factor that is a function of mode number and capsule convergence [25]. These instabilities work in tandem to amplify nanometer-scale capsule imperfections, the un-mitigated hydrodynamic growth of which can inject capsule material or cold DT fuel into the nascent central hotspot, inhibiting compression and burn.

Recent NIF experiments utilizing "high foot" laser pulses, which place the implosion on a higher adiabat (2.4) [26], have proven successful at controlling and reducing ablation front instability growth [27]. Physically, the reduction in growth appears to come from favorable RM and RT dynamics [28]. The high foot's stronger first shock increases $v_a$ during the RM phase (and therefore $\omega$) so that the most RT-unstable modes have oscillated more towards zero amplitude when they start to grow. Furthermore, $\gamma_{\rm RT}$ has been measured to be lower for the high foot pulse [28], consistent with the observation that $L_m$ is roughly 40% larger [29]. (During the RT phase, $v_a$

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is similar for low and high foot pulses with similar peak drive powers.)

High foot pulses have also produced record neutron yields and show signs of alpha-particle bootstrapping, a necessary step forward on the path to ignition [30]. A challenge of pushing these implosions to fusion power gain greater than one is the reduced convergence and compression that occurs because of the high entropy of the DT fuel. In this Letter, we describe a differential adiabat tuning methodology that seeks to maintain the ablation front stability benefits of the current high foot design, while placing the fuel on a lower adiabat to permit higher convergence and potentially increased neutron production. We present capsule design and integrated hohlraum simulations of this technique. Preliminary experiments [31, 32] support the feasibility of this approach.

One means of modifying the drive of the high foot pulse to lower the entropy of the fuel without sacrificing hydrodynamic stability is to decrease the trough of the laser pulse. The aim is to maintain the strong first shock of the high foot pulse in the capsule but allow that shock to decay, so that a weaker shock reaches the fuel. Since the start and end of the pulses are unchanged, this maintains the same favorable conditions for ablative RM and RT instability growth as the high foot design, but at a reduced fuel adiabat to allow the fuel layer to compress to higher densities. This idea is similar to the "adiabat shaping" technique proposed to stabilize direct drive ICF implosions [33–36]. However, whereas direct drive adiabat shaping seeks to improve the hydrodynamic stability at a given fuel adiabat, we seek to lower the fuel adiabat and maintain the same ablation front acceleration phase hydrodynamic properties. (It should be noted that we are not intentionally modifying the deceleration phase stability properties of the high foot design either, but this could result from the increased convergence associated with lower adiabat.)

We begin with capsule simulations to determine the radiation drive temperature ($T_r$) needed to generate a decaying first shock. We model the Si-doped CH Rev5 capsule with the radiation-hydrodynamics code HYDRA [37, 38] in a fashion similar to Ref. [39], and compare two drives: a high foot (an ideally tuned version of shot N130501 with $\alpha = 2.1$), and a new "high picket" design, which is identical except that $T_r$ during the trough (between the first and second shock launches) has been lowered from 85 eV to 65 eV and shock launch times have been adjusted. Both designs have a peak $T_r$ of 300 eV and 25% peak M-band fraction.

Figure 1 shows contours of adiabat as a function of mass coordinate (Lagragian initial radius) and time. The dotted lines indicate material boundaries, and the solid lines are shock trajectories. In all cases, shocks add entropy to the DT fuel layer [40]. The first shock of the high picket design deposits notably less entropy to the fuel than that of the high foot design, the net effect of which is a lower mass-averaged fuel adiabat by peak velocity (1.9 vs. 2.1).

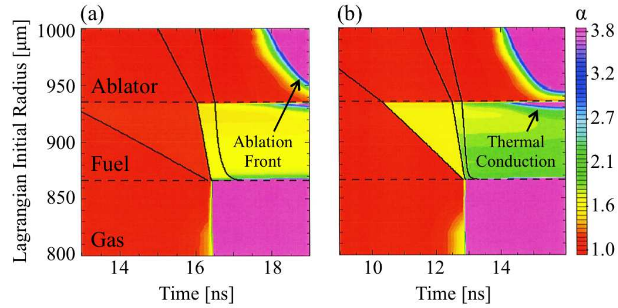


FIG. 1. A contour plot of adiabat as a function of Lagrangian initial radius and time for (a) the modified high picket and (b) and the nominal high foot designs. Dotted lines indicate material boundaries and solid lines are shock trajectories.

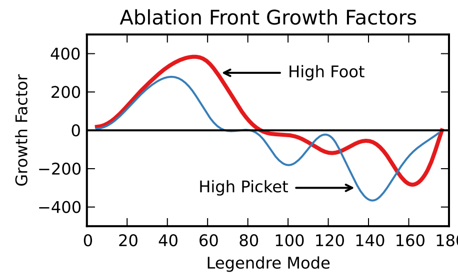


FIG. 2. Ablation front growth factor curves at peak velocity for the high foot (thick) and new high picket (thin) designs.

It is noteworthy that the second shock deposits the majority of the overall fuel entropy in the high picket design, pointing toward re-optimizing the second shock to further reduce the overall fuel adiabat. (This is consistent with the observation that the nominal high foot design's second shock is higher than optimal [41].) Figure 1 also displays the ablation front late in time, as indicated by the multicolored bar that evolves from large radii and demarcates the lower entropy ablator and high entropy blow-off plasma. The entropy profile of this ablation front region is similar for both designs. Additionally, Figure 1 shows that thermal conduction from the ablation front contributes significantly to the late-time fuel entropy, as indicated by the higher adiabat near the ablator-fuel interface.

Figure 1 indicates that the trough $T_r$ level sets the strength of the first shock as it enters the fuel layer. Lowering the trough level of the high foot, as in the hybrid high picket design, achieves the goal of reducing the adiabat of the fuel layer.

Most importantly, this reduction of fuel adiabat does not come at the price of increased ablation front growth, as shown in Figure 2, the ablation front growth factors at peak implosion velocity. That the high foot and high picket designs have comparable total growth is consistent with the observation that $L_m$ and $v_a$ for the two designs are indistinguishable during the main rise of the laser,

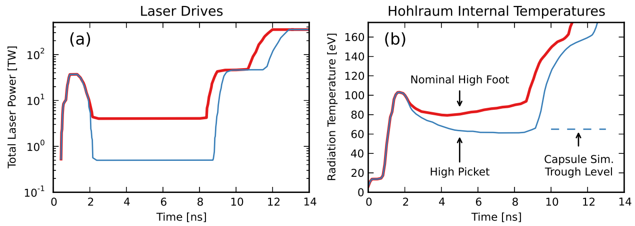


FIG. 3. a) The nominal high foot (thick line) and new high picket (thin line) laser drives. b) Hohlraum-calculated radiation temperatures for the two designs, with the high picket capsule design trough level noted.

keeping RT growth rates similar. These values, though, are different during the trough of the drive, associated with the RM phase, which may explain the minor differences seen in the growth factor curves. It should be noted that both curves are much lower than those of NIC "low foot" designs, which can exceed 1000 [3].

Lowering the drive's trough lowers $\alpha$ without increasing hydrodynamic growth. However, with indirect drive ICF, the hohlraum has a native time constant for cooling the radiation drive. Therefore, HYDRA integrated hohlraum simulations [42] were used to investigate whether hohlraum cooling can be adequate to achieve the desired drive and whether drive symmetry remains controllable.

The standard hohlraum used for the high foot campaign is a Au cylinder with 5.75 mm diameter and 9.43 mm length. A high density helium gas-fill (1.6 mg/cc) is used in order to tamp the Au wall motion as much as possible for the duration of the laser drive (14-16 ns). A "toe" is used at the start of the laser pulse, created by introducing a delay between inner and outer beams, so that the outer beams arrive at the LEH 1.2 ns after the start of the inner beams. This feature allows the low inner beam power to burn through the LEH window material, removing any density features above the quarter critical density threshold for laser-plasma instabilities when the higher outer beam power arrives. This methodology has been experimentally shown to prevent two-plasmon decay [43] during the picket, avoiding early-time generation of suprathermal electrons.

Figure 3 compares the laser pulses (a) and hohlraum radiation temperatures (b) of the high foot and high picket designs. For the high picket design, the laser power in the trough is reduced by approximately a factor of eight (which is within NIF laser specifications), and the second and third shock launch times are adjusted to maintain shock merger structure.

The lasers burn through the volume of gas before depositing their energy into the Au wall, generating the necessary radiation drive to ablate the capsule. The latency of the hohlraum results in a native decay constant associated with cooling, which can be noted by comparing the high picket's laser pulse and radiation temperature. Over the course of 3 ns, though, the hohlraum

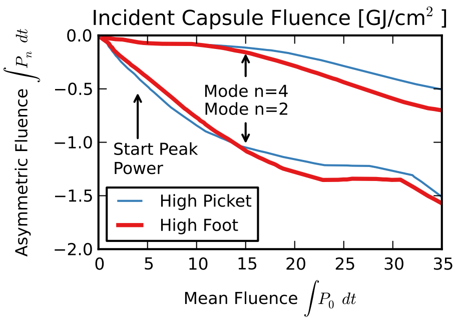


FIG. 4. Total radiation fluence incident on the capsule for Legendre modes 2 and 4 as a function of total mean fluence from integrated hohlraum simulations of the high foot (thick) and high picket (thin) laser drives. The entire laser time history is represented, moving from left to right, with the approximate start of peak power for both pulses noted.

shows the ability to cool significantly and reach the design temperature (65 eV) of the capsule simulations of Figure 1. In the hohlraum simulations, the shock for both the high foot and high picket designs is launched with a strength of approximately 5 Mbar. Both shocks decay to a level controlled by the trough drive. The high foot shock enters the fuel at 3 Mbar, but the high picket shock strength decays to 2 Mbar.

The amount of shock decay is weakly dependent upon the laser trough level. Hohlraum simulations of variations around the high picket design show that the final radiation temperature during the trough changes by roughly 10 eV/TW. This implies a floor of 60 eV, in the case where the picket is unchanged at the high foot level and the trough is turned off completely. Variations in drive will also lead to variations in the first shock's contribution to $\alpha$. In particular since $\Delta\alpha \sim \Delta P \sim \Delta(T_r^{3.5})$, $\Delta\alpha/\alpha \sim 3.5\Delta T_r/T_r \simeq 0.53$. Because $\alpha$ increases by 0.3 after the first shock (for the 65 eV drive), one expects the first shock's contribution to $\alpha$ to change by approximately 0.16 per 10 eV, or equivalently 0.16 per TW laser deviation. This is less sensitive than the NIC low foot pulse, for which $\alpha$ has been found to increase by 0.33 per TW in the trough [44]. In other words, the high picket design is not unusually sensitive to the laser trough power, since the strength of the shock is largely determined by the hohlraum and not the laser. However, the design is sensitive to the ability of the hohlraum to cool, such that a 10 eV change in final trough $T_r$ will change $\alpha$ by approximately 0.16.

Maintaining symmetry control of the implosion is important for optimizing performance [45, 46]. Drive symmetry in the reduced trough is dominated by the native geometry of the hohlraum, but since the drive during the trough is low, so too is the total asymmetric drive. Direct cone fraction tuning in the rise and plateau of the second pulse can counter asymmetries induced during the trough. Application of this technique produces a

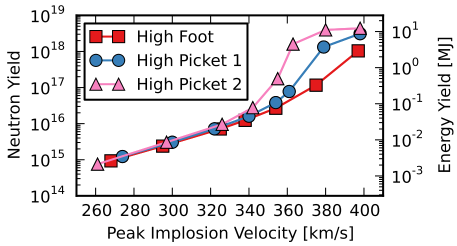


FIG. 5. One-dimensional yields as a function of peak implosion velocity for an ideally tuned high foot, a high foot with a low trough (High Picket 1) and a high foot with a low trough and a lower second shock (High Picket 2).

time history of the second and fourth Legendre moments of total incident radiation fluence similar to the original high foot design (Fig. 4). That is, drive symmetry control seems possible with the high picket design. Furthermore, our design does not show evidence of a hydrocoupling feature [47] induced by the reduced trough.

The high picket design maintains the favorable hydrodynamic instability growth properties of the high foot design while reducing the overall fuel adiabat, allowing increased compression and improved ignition margin, which can be seen in Figure 5, the one-dimensional capsule yields as a function of peak implosion velocity for the ideally tuned high foot and two modifications to the high foot: our lower trough design (High Picket 1) and another design (High Picket 2), in which the second shock drive temperature has been lowered by 40 eV (in addition to lowering the trough, thereby further reducing $\alpha$ by 0.2). All designs are predicted to ignite (in 1D) with a sufficiently high drive, but the threshold for ignition varies. The high foot pulse requires a velocity of roughly 390 km/s to produce 1 MJ of energy, right at the 380-400 km/s achieved to date [48]. Our designs ignite below this level. Figure 5 also demonstrates that further improvements could be achieved by reducing the second shock strength as well as the trough. In essence, these modest modifications to the high foot pulse increase the margin for ignition, without sacrificing on ablation front growth.

Efforts are also underway to optimize and to adopt similar techniques for other designs. For alternate ablators (such as high density carbon or beryllium), an additional constraint may be the minimum shock pressure needed to melt the ablator. With low-gas-filled and near-vacuum hohlraums, more extreme shaping be possible, because hohlraums with less gas appear to heat and cool quicker. And since the primary hohlraum cooling mechanism is energy loss through the LEH windows, hohlraum geometry is also likely to influence indirect drive adiabat shaping.

Our simulations indicate that sufficient hohlraum cooling can be achieved in indirect drive ICF such that differential adiabat tuning may be possible. Initial experiments [31, 32] on a pulse similar to the High Picket 2 design (but with a trough level of 1 TW instead of 0.5) have shown the general viability of this approach: lowering the trough and second pulse can reduce the fuel adiabat without adversely affecting hydrodynamic growth or shape control. The quantitative details of these experiments are to be presented elsewhere, but briefly, VISAR [49] shot N140718 measured a decaying first shock and cooling $T_r$ profile consistent with a reduction of $\alpha$ by 0.2-0.3, Hydro Growth Radiography [50] experiment N140818 showed high-foot-like growth for Legendre modes 60 and 90, 2DConA [51] shot N141028 measured a slightly prolate in-flight shell, indicating sufficient inner beam propagation for capsule shape control, and cryogenic DT shot N150115 showed enhanced compression and yield without evidence of ablator-fuel mix.

## ACKNOWLEDGMENTS

The authors wish to thank the entire NIF ICF team and in particular D. Callahan, D. Casey, D. Hinkel, O. Hurricane, O. Landen, J. Milovich, N. Meezan, H. Robey, V. Smalyuk and R. Tommasini for useful discussion, guidance and commentary. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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