

Hot spot formation and stagnation properties in simulations of direct-drive NIF implosions

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Abstract. We investigate different proposed methods of increasing the hot spot energy and radius in inertial confinement fusion implosions. In particular, shock mistiming (preferentially heating the inner edge of the target's fuel) and increasing the initial vapor gas density are investigated as possible control mechanisms. We find that only the latter is effective in substantially increasing the hot spot energy and dimensions while achieving ignition. In all cases an increase in the hot spot energy is accompanied by a decrease in the hot spot energy density (pressure) and both the yield and the gain of the target drop substantially. 2D simulations of increased vapor density targets predict an increase in the robustness of the target with respect to surface perturbations but are accompanied by significant yield degradation.

1. Introduction

In ICF, spherical implosions concentrate the kinetic energy of the imploding fuel shell and convert it to internal energy of a hot spot and compressed fuel layer when the shell stagnates at its center. This process is inefficient: only $\sim 2\%$ [1] of the absorbed energy ends up in the stagnated hot spot. As the hot spot is solely responsible for igniting the rest of the fuel, its energy content is crucial in determining the success and gain of the target. In conventional central-ignition icf, the hot spot is heated primarily by pdV work of the imploding fuel shell. The gas vapor initially inside the target makes up only a small fraction of the hot spot ($\sim 5\%$), the rest being contributed by the inner edge of the initial fuel shell.

Models describing the scaling and evolution of a pre-established hot spot have been offered [2, 3], but do not address its origin. For instance, they are silent about which parts of the inner fuel edge participate in the hot spot as opposed to comprising the compressing fuel. These models of the hot spot energy predict a scaling like $E \sim \alpha^a p^{-b} V^{-c}$ where α is the fuel shell adiabat, p is the drive pressure, V is the implosion velocity, and a, b , and c are model-dependent (positive) constants. We will assume that the parameters α, p and V are fixed here, as well as the mass and geometry of the target and the laser energy. We instead are interested in the parameters that form the “constant of proportionality” in that scaling; we'd like to know what other factors can control the hot spot in a stagnated target. We will investigate two approaches: changing the timing of the drive laser pulse to preferentially shock heat the inner edge of the fuel layer, and changing the initial gas density inside the target.

Altering the pulse timing is a common procedure for most laser facilities and is limited only by the accuracy of the timing system. The idea behind this is to cause shock collisions in the compressed fuel or shocks in the rear rarefaction, and induce more heating of just the innermost fuel shell which forms the bulk of the hot spot. The hope is that a significant change in the hot spot assembly might be induced, while changing the rest of the implosion in only a minor way. In contrast, adjusting the vapor density is usually done by fielding the target at a different initial (cryogenic) temperature. Such an approach



presents implementation challenges, since the highest gas density that can be reached while still using a solid-DT fuel layer (at the 19.79°K triple point) is about 6.2 mg/cm^3 [4] a higher fielding temperature, and the DT-ice layer melts. A low-density foam matrix can be used to support such a liquid layer in place [5]. The decrease in the DT fuel density in melting is countered by the additional density contributed by the foam matrix and the resulting fuel-foam matrix has about the same density as the solid DT ice. A previous similar study investigating indirectly-driven targets concluded that this substitution is not a major design consideration [6]. Here we ignore this effect and consider the ice layer to remain the same (in composition and density) through the range of vapor densities considered. As a result the yields reported in this analysis may be viewed as an upper-limit.

We will address two questions: the first is whether we can increase the radius, energy and/or pressure of the hot spot while still achieving ignition. Using the FASTRAD3D radiation hydrocode [7], we investigate this with a series of 1D studies varying the laser pulse characteristics or the vapor density. Secondly, we'd like to know if the changes induced in the first step have a positive effects on the robustness, stability and/or performance of the target. 2D simulations using FASTRAD3D will provide this answer.

It is worth noting that the results can depend on how the hot spot is defined. Because we are primarily interested in finding a robust ignition, we define the hot spot as the central region where the ion temperature exceeds 4 keV when it either exceeds 0.3 gm/cm^2 or reaches a maximum areal mass less than 0.3.

2. Hot spot formation: 1D results

We start with a tuned design that is consistent with the NIF laser parameters. A relatively low initial aspect ratio target previously studied for shock-ignition [9] was converted to conventional central ignition by removing the final shock spike pulse and raising the compression power. Fig. 1 shows the target with the 1 MJ , $\lambda = 0.351\text{ }\mu\text{m}$ drive laser pulse ($\sim 740\text{ kJ}$ with $0.248\text{ }\mu\text{m}$ light) and in-flight adiabat ~ 2 which produces about 73 MJ in yield; the pulse timings shown were found to maximize the target yield.

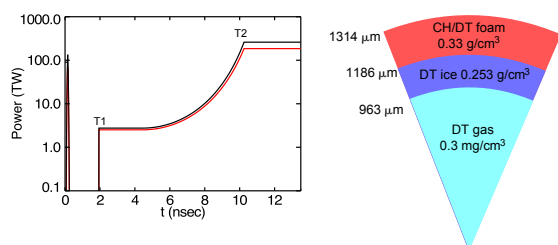


Figure 1. The baseline target design for this study. The pulse shown is for laser wavelengths $0.351\text{ }\mu\text{m}$ (black) and $0.248\text{ }\mu\text{m}$ (red). Times T_1 (1.94 ns) and T_2 (10.25 ns) mark the onset of the pulse foot and the main power, respectively. A single zoom in the laser spot diameter to the concurrent critical surface radius occurs at T_2 .

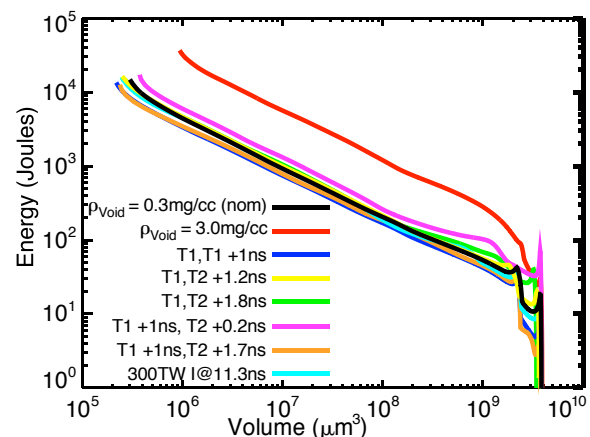


Figure 2. The Energy of the hot spot as it shrinks in volume. The black line is the baseline design.

First we consider the consequence of increasing the initial fill gas density by over an order of magnitude. The additional gas results in a substantial increase in the radius and energy contained in the hot spot (Fig. 3). Conversely, the hot spot pressure ($\sim E_{hs}R_{hs}^{-3}$) and the target yield decrease monotonically. A major portion of the yield decrease is due to the smaller assembled ρR caused by the larger hot spot. However there is still ignition and appreciable yield when the gas density is an order of magnitude larger than nominal, and the hot spot radius has increased about 50%. Here we might expect a favorable tradeoff between yield and target robustness.

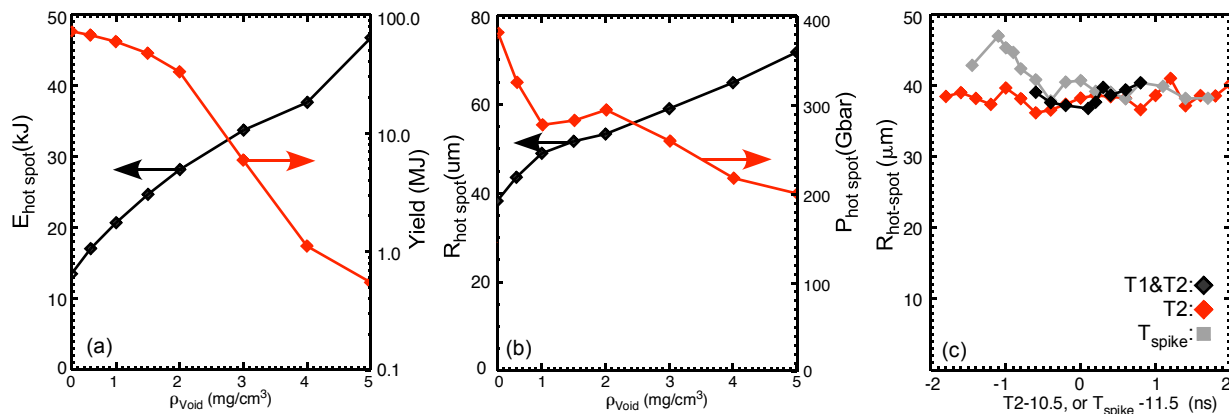


Figure 3. The response of the hot spot parameters to the increased vapor density in the initial target interior: (a) and (b). (c) shows the resulting hot spot parameters when pulse timing is changed or a spike pulse is added. In (c), data is shown at all points where the yield is at least 10% of the baseline.

Next we investigate the consequences of deliberately mistiming and creating shocks. Three variations were tried: (1) the foot (at time T1) and the main drive (onset at T2) were together delayed or advanced relative to the initial spike shock; (2) the main drive (T2) was delayed / advanced relative to the spike and foot onset; and (3) an additional picket pulse (250 psec FWHM, 300 TW) was added in addition to the baseline pulse at times T_{spike} between 8.8 and 13.2 nsec. In all cases, the simulations predict the resulting hot spot radius to vary less than $\sim 10\%$ (Fig. 3c) when significant yield occurs. Other hot spot parameters vary in a similar minor way. Although the fuel from the affected inner edge forms the bulk ($> 95\%$) of the subsequent hot spot, little effect is seen from the attempt to preferentially heat it just before the implosion progresses. This is not just an artifact of ignition truncating a growing hot spot: similar minor effects are seen in an unignited hot spot when TN burn is artificially turned off.

The reason for this is shown in Fig. 2, which plots the total energy of the mass that forms the hot spot as a function of its volume. This energy is due to the PdV work done on the hot spot by the boundary pressure. In all the cases of mistiming the pulse, there is an initial jump to a higher pressure at the hot spot boundary as the material is shock heated. However, the material at the boundary then expands due to the subsequent rarefaction wave, and the pressure soon drops to about the same level as it would be without the shock mistiming. The net effect over most of the implosion is little difference in this energy. In contrast, raising the initial vapor density by a factor of ten (the upper red line in the figure) allows the pressure to maintain a higher level throughout the implosion, (the rarefaction is more contained by the higher density), and the energy put into the hot spot can be significantly increased.

3. Multidimensional robustness

In the cases where we were successful in increasing the hot spot dimensions (by increasing the initial vapor density), we then checked the robustness of the larger hot spot radius / lower convergence ratio by using high-resolution 2D simulations. In all cases, a $1 \mu\text{m}$ RMS roughness was put on the inner DT ice layer, while we varied the outer surface roughness from $0.1 \mu\text{m}$ to $0.4 \mu\text{m}$. The spectral distribution of these perturbations is the same as in Ref. [1] and is meant to emulate the “NIF spec”. The laser drive is uniform. Sample images of the density and temperature at stagnation are shown in Figs. 4. For this perturbation level (and others simulated here) the larger hot spot does not correlate with a more symmetric stagnation. Over the full set of simulations, we find that increasing the target vapor density always results in a lower yield (c.f. Fig. 5a). As the perturbation level increases, both the yield and its perturbation variance (slope) are significantly smaller. However as a ratio of the 1D yield (Fig. 5b), the decrease in both is milder at higher vapor densities.

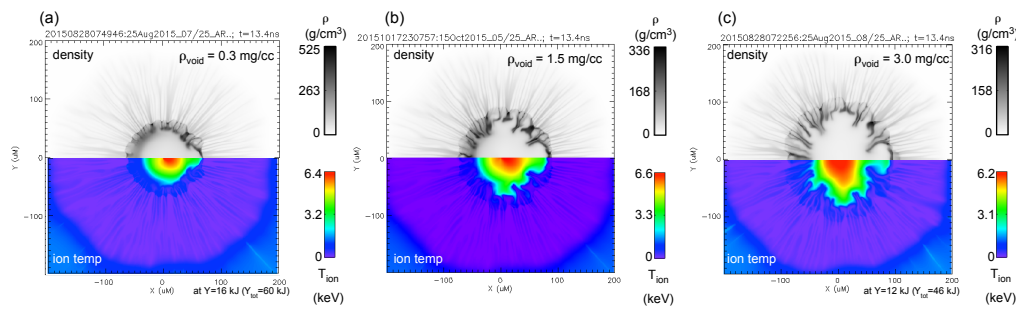


Figure 4. The mass density (top, grayscale) and ion temperature (bottom, color) images from the 2D simulations at the approximate time of hot-spot ignition for increasing vapor density: (a) 0.3 mg/cm^2 ; (b) 1.5 mg/cm^2 ; and (c) 3 mg/cm^2 . All simulations started with $1 \mu\text{m}$ inner ice surface roughness and $0.4 \mu\text{m}$ outer surface perturbations.

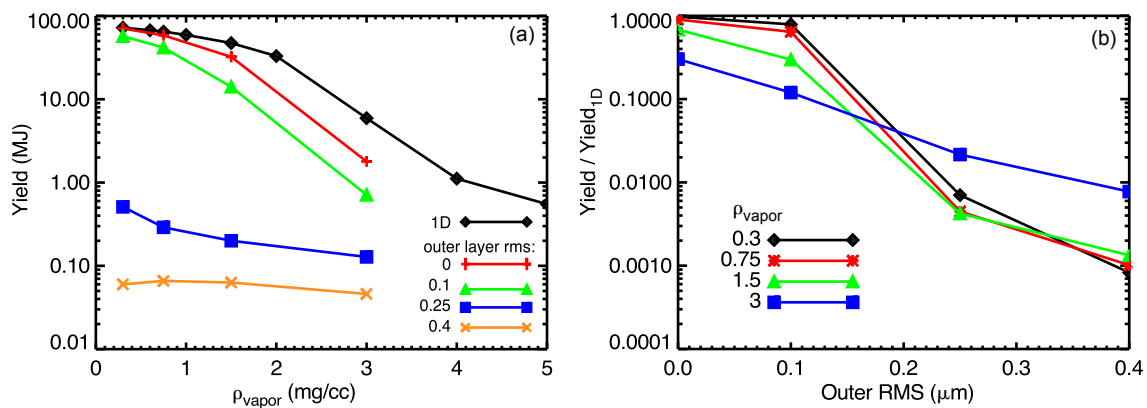


Figure 5. (a) The 2D yield degradation as a function of vapor density for $1 \mu\text{m}$ RMS inner surface ice roughness and different outer surface perturbations; (b) the yield/1D-yield as a function of the outer surface perturbation level.

Acknowledgments

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