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Cheng, Baolian
Bradley, Paul Andrew
Finnegan, Sean Michael
Thomas, Cliff

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Fundamental factors affecting thermonuclear ignition

Baolian Cheng,[1] Paul A. Bradley,[1] Sean M. Finnegan,[1] Cliff A. Thomas[2]
[1] Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA;
[2] Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14623, USA

Recent inertial confinement fusion (ICF) experiments on the National Ignition Facility (NIF) have improved performance and interpretability. These results help us address hydrodynamic efficiency, pusher adiabat, tamping, and hot-spot confinement as they pertain to criteria for ignition. We present requirements for propagating burn that are stringent compared to existing literature. The effects of the pusher adiabat on the energy partition for the cold and hot DT are addressed, as well as the persistent discrepancy between the observed and simulated neutron down scattering ratio (DSR). The required energy for achieving ignition on NIF and paths forward to optimize or increase the capsule yields for given laser energy are also discussed.

Keywords: Inertial confinement fusion, thermonuclear ignition

1. INTRODUCTION

Performance was recently improved on the National Ignition Facility (NIF) in shots using the BigFoot platform, and implosions sharing many of same characteristics [1–3]. As shown in Figure 1, this follows a series of improvements made to indirect-drive implosion over the last ten years. The first significant increase in neutron yield from 10^{13} to 10^{15} was achieved by changing the foot level from four shock pulse-shape (low foot) [5] to three shock pulse-shape (high foot), and correcting issues in target fielding and initial conditions (e.g., the accumulation of condensates on the hohlraum entrance hole). Rayleigh-Taylor and Richtmyer-Meshkov instabilities were reduced [6, 7], and reproducibility was significantly improved. The second large yield increase from 1×10^{15} to 7×10^{15} can primarily be attributed to the use of depleted uranium (DU) hohlraums, increasing energy and power, improved target quality, and reduced instabilities. The third yield jump was to raise the neutron yield from 7×10^{15} to 10^{16} by adapting a series of design changes [2–4, 8–10, 12], such as the reduction in fill tube diameter [2, 3], changing the ablator from CH to high density carbon (HDC), pulse shape from high foot to BigFoot [1, 4, 11], holhraum gas density from high to low [12], and peak implosion velocity from 300 μm/ns to around 370 μm/ns and higher. In net, these changes largely improved the implosion quality and the energy coupled to the capsule.

More specifically, the use of HDC as the ablator material has forced the shortening of the laser pulse, and the low density gas fill hohlraum (0.3 mg/cm^3) has reduced laser plasma instabilities at high power, lessened hohlraum wall motion, and provided a well-understood radiation source. Moreover, a 12 Mbar or greater first shock has greatly reduced phase coexistence in the ablator (causing uncertainty) and further increased stability. All of these improvements happened at once together with a larger laser entrance hole (LEH), cone and quad split pointing, and higher adiabat, and resulted in more symmetric implosions at higher velocities and yields.

As the performance of the capsule once again reached a plateau regardless of the magnitude of the high peak implosion velocity, it is reasonable to ask several questions: (1) How far is the NIF from achieving ignition? (2) How much more laser energy would be needed to upgrade NIF so as to achieve ignition? And (3), is there a novel design change or changes that could lead to several additional jumps in neutron yield? In order to answer these critical questions and have an informed perspective about NIF and its future, we revisit the necessary condition of thermonuclear (TN) ignition and reanalyze the capsule having the record yield.

2. THE NECESSARY CONDITION

Achieving thermonuclear ignition and high yield requires self-sustained thermonuclear burn in the

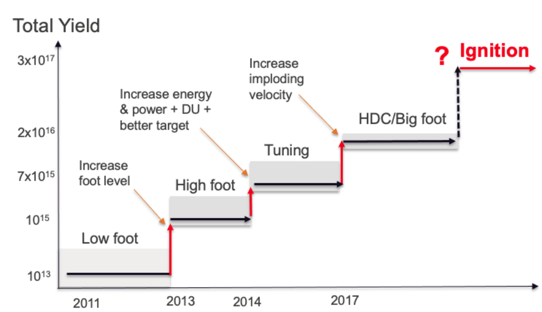

FIG. 1. Total neutron yield of NIF DT ice layered shots versus time. The first jump in yield is due to a change of foot level from a low foot to high foot laser pulse. The second is due to the increase of energy and power, improved targets, depleted uranium (DU) hohlraums, and more design tuning. The third yield jump is due to changing to a HDC ablator, BigFoot laser pulse, low gas fill hohlraums, and reduced fill tube diameter, etc. (noticing that not all of shots have these changes simultaneously).

deuterium-tritium (DT) fuel. The net nuclear-energy deposition (ΔQ_{nuc}) in the DT must be double the energy (E) of the DT (i.e., the DT-energy increase, ΔE, from the thermonuclear DT reactions equals the DT energy itself for self-heating and self-sustained) to offset the energy loss from various sources (e.g., bremsstrahlung radiation, electron thermal conduction, blackbody radiation, etc.) in order to maintain the DT temperature at or above the critical ignition temperature during the hydrodynamic disassembly time (τ_H) in addition to the DT PdV work [13, 16]. That is,

$$\Delta Q_{nuc} \geq \Delta E + P\Delta V. \quad (1)$$

In this formula,

$$\Delta Q_{nuc} = W_\alpha \frac{\partial N_D}{\partial t}\tau_H = W_\alpha \frac{N_D N_T < \sigma v >}{V}\tau_H, \quad (2)$$

where $W_\alpha \equiv 3.52 f_\alpha + 14 f_n$ MeV is the energy deposited into the hot DT per fusion, which is equal to the sum of a fraction (f_α) of the α-particle kinetic energy 3.52 MeV and a fraction (f_n) of the fusion neutron energy 14 MeV. Normally $f_n \sim 0$ because the mean free path of the 14 MeV neutrons is much larger than the hot spot radius R_{hs}. f_α is determined by the formula given in Ref. [14]. N_D and N_T are the number of D and T nuclei (in moles), respectively; V is the volume of the hot DT and $< \sigma v > \approx C_{DT} T^b$ [16] is the DT nuclear reaction rate, with the gas temperature T in keV and the constant C_{DT} has a value of $8.872 \times 10^{-21}\text{cm}^3/(\text{s}\cdot\text{keV}^5)$ for $b = 5$ and $2.3 \times 10^{-20}\text{cm}^3/(\text{s}\cdot\text{keV}^4)$ for $b = 4$. For NIF capsules at 3 to 5 keV, the fitting power index $b \simeq 4$.

Here, it is worth mentioning that the requirement of energy doubling is critical for ignition capsules having self-sustained DT burn at or above the ignition temperature against all of the known and unknown energy losses. Without energy doubling, there will not be e-folding growth in energy and the DT temperature would soon drop below the critical ignition temperature due to various energy losses. The energy of the hot DT gas is given by $E = E_{mat} + E_{rad}$, in which $E_{mat} = 3(N_D + N_T)kT$ represents the matter energy and $E_{rad} = aT^4V$ the radiation energy. k is the Boltzmann constant and a the blackbody radiation constant. We have also assumed a fully ionized gas, $N_D + N_T \simeq N_e$, where N_e is the number of electrons.

The gas PdV work has the expression

$$P\Delta V = \rho_{DT}\epsilon_I(\gamma - 1)\Delta V. \quad (3)$$

Here, $\epsilon_I \equiv (E - aT^4V)/M_{DT}$ is the specific internal energy of the hot DT, ρ_{DT} the mass density and $M_{DT} \equiv \rho_{DT}V$ the total mass of the hot DT. γ is the adiabatic index of the plasma-radiation mixture.

Substituting Eqs. (2), (3) and E into Eq. (1) gives

$$W_\alpha \frac{N_D N_T < \sigma v >}{V}\tau_H \geq E[1 + (1 - \frac{aT^4V}{E})(\gamma - 1)\frac{\Delta V}{V}]. \quad (4)$$

Dividing through by the left hand of Eq. (4) and using the energy reproduction time $\tau_{rep} \equiv E/(W_\alpha N_D N_T < \sigma v > /V)$ [13, 15, 16], we obtain

$$1 \geq \frac{\tau_{rep}}{\tau_H}[1 + (1 - aT^4V/E)(\gamma - 1)\frac{\Delta V}{V}]. \quad (5)$$

During fusion in a capsule, the expansion of the DT gas volume (ΔV) in one hydrodynamic disassembly time is very small relative to the total gas volume: $\Delta V/V \ll 1$. Together with $aT^4V/E < 1$ and $(\gamma - 1) < 1$, the second term on the right side of Eq. (5) is much less than 1 and is therefore negligible compared to the first term (if not, this term makes it harder to meet criteria). Thus, Eq. (5) reduces to

$$\tau_{rep} \leq \tau_H, \quad (6)$$

where the hydrodynamic disassembly time $\tau_H \equiv R^*_{hs}/C^*_s$, in which R^*_{hs} is the effective radius of the hot DT. For spherical symmetry, $R^*_{hs} = R_{hs}$ (the 1D radius of the hot spot), for irregular hot spot, $R^*_{hs} \simeq R_{hs}\tilde{g}$, here $\tilde{g}$ is a shape factor having value of 1 for spherical and < 1 for non-spherical hot spots [21]. $C^*_s = C_s/f_T$ is the effective sound speed, where $C_s \simeq 2.778 \times 10^7\sqrt{\gamma T(keV)}$ cm/s represents the sound speed in the hot DT and f_T the tamping factor. Equation (6) is the minimum (or less conservative) necessary condition for the DT-burn in the capsule to be self-sustained.

We would like to point out that the energy reproduction time is an important time scale in fusion. It is the time required for an equal amount of energy to be liberated by thermonuclear DT reactions or the time required for the energy of the system to double itself (e-folding) and have a self-sustained thermonuclear burn and fuel temperature at or above the critical ignition temperature as a result of DT interactions. This quantity measures the energy reproduction rate of the system. It is a useful concept for comparing the competing processes of heating vs. cooling at various densities and temperatures per unit time in a system. By comparing the energy reproduction time with the time required for sound to move cross a system of feasible size, we gain idea of what energy and temperatures are required at various densities. Condition (6) guarantees ignition and e-folding growth of the energy. For capsules with explicit energy loss rate $\dot{Q}_l \equiv dQ_l/dt$, for example, the energy loss rate from bremsstrahlung emission and electron heat conduction, the general expression of the energy reproduction time has form $\tau_{rep} = E/(W_\alpha N_D N_T < \sigma v > /V - \dot{Q}_l)$ [16, 20]. Clearly, any energy loss would prolonger the energy reproduction time of the system.

Condition (6) is stronger than the necessary conditions, $dT/dt > 0$ and $d^2T/dt^2 > 0$, introduced by Springer et al. [30, 31], which do not ensure self-sustained TN burn. This is because (a) $dT/dt > 0$ does not specify if the DT temperature reaches the ignition level, (b), not all of the energy losses are taken into account, and (c), condition $d^2T/dt^2 > 0$ only assures that the condition at $dT/dt = 0$ is a minimum and not a maximum. According to the later condition, the high performers in the recent NIF shots would be quite close to the ignition as suggested by a number of authors.

However, by condition (6), none of the NIF shots is near the ignition threshold. Even for the NIF high performer N180128, the nuclear reproduction time is still significantly (2.5 times) longer than the hydrodynamic disassembly time. Thus, there is no self-sustained TN burn in experiments on NIF. All of the NIF shots, in fact, require significant improvements if they are to approach requirements.

Substituting the general expression of τ_{rep} and $\tau_H \equiv R^*_{hs}/C^*_s = R_{hs}\tilde{g}f_T/C_s$ into condition (6) leads to the $\rho R - T$ condition of ignition [16]

$$\rho_{hs}R_{hs} \geq \frac{[(1+d)^2/d][3kT + E_{rad}/n_{DT}]C^*_s A_{DT}}{[\langle\sigma v\rangle W_\alpha - \dot{Q}_l(1+d)^2/(dn^2_{DT})]\tilde{g}N_A}, \quad (7)$$

where $n_{DT} \equiv n_D + n_T \equiv \rho_{DT}N_A/A_{DT}$, $d = N_D/N_T$, $n_D/n_{DT} = d/(1+d)$, and $n_T/n_{DT} = 1/(1+d)$. N_A is the Avogadro's number and A_{DT} the average atomic mass of the DT mixture. Condition (7) can be further reduced to three conventional forms in terms of observable quantities: (1) pressure requirement, $P_{hs}(Gbar)\tau_H(\mu s) \geq 0.475/[T^2(keV)\tilde{g}f_T]$; (2) minimum hot spot mass $M^{min}_{hs} \geq 92.34 \times [R_0(cm)/C_f]^2/[T^{2.5}(keV)\tilde{g}f_T]$ g; and (3) burn fraction $\phi \geq \rho_{hs}R_{hs}/[\zeta(T) + \rho_{hs}R_{hs}]$; where C_f is the convergence ratio and $\zeta(T)$ the burn parameter [16]. The required minimum hot spot mass at various ion temperatures and convergence ratios is given in Table I.

Convergence Ratio $C_f = R_0/R_{hs}$	Minimum hot spot mass $M^{min}_{hs}(\mu g)$ with temperature 4 keV	5 keV
40	18	10
35	24	13
30	32	18
27	40	23
25	46	26
20	72	41
15	128	73
10	289	165

TABLE I. The required minimum hot spot mass for pure DT at various ion temperature and convergence ratio.

Table I reveals the great challenge for the NIF point design to form the required minimum hot DT mass for ignition. Because implosion symmetry and ignition threshold decrease with the increase of convergence ratio, maintaining good symmetry is easier at low convergence but lead to a higher ignition threshold, for example, a higher minimum hot DT mass. Recent simulations of the polar direct drive (PDD) design on NIF show great promise for producing the required hot DT mass at a low convergence ratio [36]. Even so, this approach challenges that would have to be overcome. For example, the symmetry of direct-drive implosions can be greatly modified by cross beam energy transfer (CBET) [37, 38], and mitigation requires more laser bandwidth or wavelength de-tuning than is presently available. The current phase plates are also non-opitimal, and the beam geometry makes it difficult to exploit the available energy. Thus, shots using direct-drive require careful design, and would be expected to benefit from upgrades to the facility.

Also, it is worthwhile to point out that any small amount of mix will greatly increase the ignition threshold [19] and make ignition much more difficult. High-Z mix changes the energy partition between hot spot and pusher, and also dilutes the density of the DT in the hot spot. In addition, the shape factor $\tilde{g}$ usually is much less than one in the presence of mix caused by instabilities [18].

3. NIF IGNITION STATUS

In order to determine if NIF high performing capsules are close to achieving ignition, we analyze the NIF high yield shot N180128 and compare our analysis with the criteria. In N180128, the capsule has a measured neutron yield $\sim 2 \times 10^{16}$, hot spot radius $\sim 30.8\,\mu m$ and an average ion temperature $\sim$ 4.9 keV. The neutron down scattering ratio (DSR) [22] for this capsule is about $3.1\% \pm 0.1\%$ and the peak implosion velocity is approximately $430 \pm 10\,\mu$m/ns. Using these numbers, we can estimate the average nuclear energy reproduction time in the capsule during the TN burn, $\tau_{rep} \simeq E/[N_D N_T < \sigma v > W_\alpha/V] \sim 86$ ps. Instead of being shorter, τ_{rep} is significantly longer (∼2.21× bigger) than the hydrodynamic disassembly time, $\tau_H = R_{hs}/C_s \sim 39$ ps, of the capsule. Note that in our analysis, we have used $f_T \simeq 1$ (see Section 6). Also, we have purposely taken $f_\alpha \simeq 1$ to overestimate the alpha-heating and $\tilde{g} \simeq 1$ to underestimate the hydrodynamic cooling and energy loss for N180128. The burn fraction (ϕ) in this capsule is only 0.117%, which is one sixth of the required fraction ($\simeq$ 0.7%) for ignition [15, 20].

According to these numbers, the nuclear heating rate in this capsule is less than 1/2 of the hydrodynamic cooling rate and, hence, the TN burn in this high yield NIF shot is not self-sustained. Fig. 2 shows the NIF experimental data relative to the ignition criteria Eq. (7) on the $\rho R - T$ plane. The solid line represents the ignition curve when one ignores energy losses, while the dashed line denotes the ignition curve taking into account losses from bremsstrahlung radiation and electron thermal conduction. The black circles are the NIF experimental data. The red star represents the high yield shot N180128 below which is the shot N190721, which had laser energy 1.3 MJ and was the sub-scale (~ 0.8) version of N180128. We see from the figure that the NIF shots fielded to date are still far from ignition in its current configuration, and

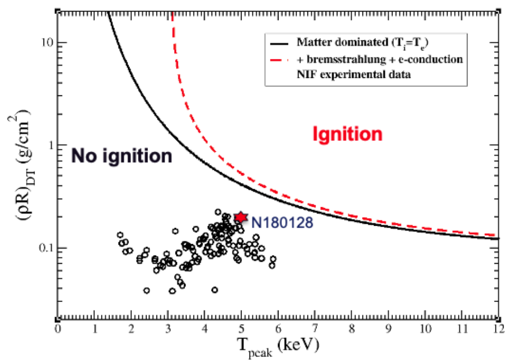

FIG. 2. NIF data compared with the Ignition curve on the $\rho R - T$ plane. The solid black line represents the ignition curve without radiation or conduction losses. The red dashed line denotes the ignition curve in the presence of energy loss by radiation and electron heat conduction, where thermal equilibrium between ions and electrons are assumed. Any small amount of mix will push the ignition threshold higher [32]

unlikely to achieve high gain without a large upgrade in driver energy or a breakthrough in capsule design.

Here we would like to point out that the hot spot areal density of the NIF capsules has been often overestimated by using the measured neutron yield, an average over 4π, and the full burn width at half maximum (FWHM) in the analysis [23, 31] while the data suggests that the areal density has significant 3D variation [21, 29, 30]. The resultant error in the hot spot areal density can be as large as a factor of 2.

Theoretically speaking, if a capsule was close to ignition, the following signatures would need to be observed: (1) a nuclear energy reproduction time shorter than (or at least close to) the hydrodynamic disassembly time; (2) A sharp and narrow peak neutron flux so that the full burn width of the capsule is close to the full burn width at half maximum as demonstrated in Fig. 3; (3) the FWHM would be less than 50-60 ps for the current NIF capsule designs; and (4) a burn fraction close to 1.65% [32].

Although the NIF is not yet close to ignition, it may be possible to double or triple the neutron yield of N180128 through improvements of the fundamental factors in TN burn, as we describe in the following sections. From the minimal energy implosion theory [13], the product of the hot spot pressure (P_{hs}) and the hydrodynamic disassembly time (τ_H) is expressed in terms of the implosion parameters

$$P_{hs}\tau_H = P_0\Big[\frac{\gamma_p}{(3\gamma_p-1)\epsilon_0}\eta_L\eta V_{imp}^2\Big]^{\frac{\gamma_p}{\gamma_p-1}}\frac{R_{hs}}{C_s}\tilde{g}f_T \qquad (8)$$

where P_0 and ϵ_0 are, respectively, the pressure and specific internal energy of the pusher at the time of peak implosion velocity (V_{imp}), γ_p is the effective adiabatic index [33] of the pusher that is nonlinearly related to

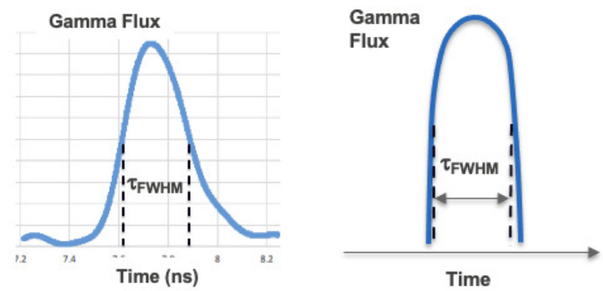

FIG. 3. The gamma flux in an un-ignited/ignited capsule. Left plot represents the gamma flux in a typical NIF un-ignited capsule where the full burn width is about two times longer than the FWHM width. The right figure illustrates the gamma flux in an ignited capsule where the full burn width is approximately equal to the FWHM width.

the DT adiabat [15]. η_L is the conversion efficiency of the laser energy to the pusher kinetic energy and η the conversion efficiency of the pusher kinetic energy to the internal energy of the total stagnated mass. These two coefficients account for the energy losses from the system during the implosion process. Eq. (8) reveals that the performance of the capsule not only directly depends on the peak implosion velocity, but also on other essential factors, such as the pusher adiabat, tamping factor, hot spot geometries, pusher symmetry, and pusher pressure at the time of peak implosion velocity.

Over the course of ten years of experiments, the NIF has made significant progress on several metrics for ignition, such as increasing the peak implosion velocity and ablation pressure; reducing the diameter of the fill tube and instabilities from interfaces and the tent; improving capsule manufacturing and the hot spot shape; reducing the preheat from hot electrons, and increasing the energy coupling with the low gas fill hohlraum. However, for a given laser energy, reducing hydrodynamic instability [34] by increasing foot-level comes at the cost of a higher pusher adiabat. Also, increasing peak implosion velocity comes at the cost of a reduced pusher mass.

4. PUSHER ADIABAT

High pusher adiabat is a principle source of reduced compression and reduced performance. It determines the energy and mass partition between the hot spot and the pusher (cold fuel and remaining ablator) during capsule implosion. The energy into the hot spot in high pusher adiabat (e.g., $\alpha \sim 3$) is only one half of the energy into the hot spot if the pusher was at a low adiabat ($\alpha \sim 1.5$) [20]. At the same time, the hot spot mass and pressure in a high adiabat capsule are significantly less than that of a low pusher adiabat capsule [20]. The ratio of specific implosion kinetic energy to the specific internal energy of the capsule (hotspot + cold fuel) is a good measure of the efficiency of the energy conversion and generation in an ignition capsule during its hot spot formation. For the recent high yield capsules, the ratio of the specific internal to kinetic energy is around 0.15 ± 0.015 (The ratio for N180128 and N190721 are 0.16 and 0.15, respectively). If the pusher adiabat in the same capsules were low, the ratio of the specific energy could be enhanced to as high as 0.3 [39].

Although the pusher adiabat cannot be directly measured, it can be inferred from the ratio of the radius of the hot spot to the outer radius of the pusher (R_p) using physics relationship obtained from the minimum energy theory [13, 15, 16, 20]: $R_{hs}/R_p = 1/[1 + 2\gamma_p/(\gamma_g - 1)]^{1/3}$, where γ_g is the adiabatic index in the hot spot. For $\gamma_g = 5/3$, this formula gives $R_{hs}/R_p \approx 0.61$ if $\gamma_p = 5/3$ (low pusher density, adiabat ~ 3) and $R_{hs}/R_p \approx 0.465$ if $\gamma_p = 3$ (high pusher density, adiabat ~ 1.5) . Fig. 4 displays the ratios of the hot spot radius to the outer radius of the remaining ablator taken from the neutron image data of more than 120 NIF experiments. The result shows that nearly all of the

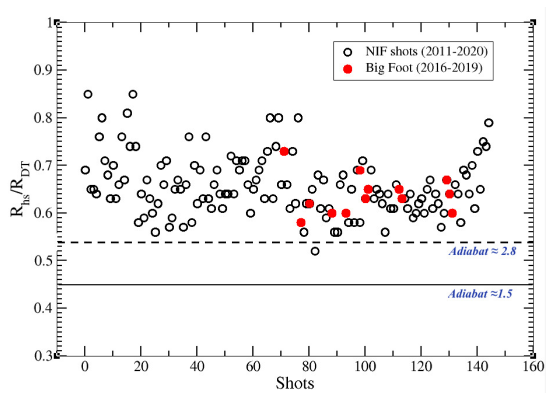

FIG. 4. The measured ratio of the hot spot radius to the outer radius of the DT fuel obtained from the neutron images in the NIF experiments. The typical error bar for the measured ratio is ±0.05. The red solid circles represent the NIF big foot shots and the black open circles are the rest of the NIF shots.

NIF shots have radius ratios greater than 0.55, which is larger than 0.465 – the value one expects when the pusher adiabat is low. Therefore, the observed neutron image data indicate that the pushers in all NIF experiments (low/high/BigFoot) are on a relatively high adiabat.

The difference between the low foot and high foot NIF experiments is that the former probably have an unintended high adiabat caused by larger than expected RT and RM instabilities, hot electrons, asymmetries, etc., while the high foot shots have an intentionally high adiabat through the pulse shape (thereby minimizing the adiabat increase caused by interfacial instabilities). As we know, the BigFoot is meant to be adiabat ~ 4 but looks no different than all other data, most of which is supposed to have an adiabat of 1.5-2.5. Interestingly, NIF data suggest that the pusher adiabat in the most recent 50 NIF ignition experiments might be slightly lower than the pusher adiabat of the low foot capsules tested earlier, as shown in Fig. 4.

Additional evidence that all NIF capsules are on high adiabat comes from the measured neutron down scattered ratio (DSR), which is persistently lower than simulations predict, as shown in Fig. 5 [24]. Recent post shot simulations [28] appear to match experiments with CH and HDC ablators to $\sim 30\%$ in burn-averaged temperature and DSR. Agreement is comparable or even improved for the most recent implosions using beryllium (see later of the section), but may not be statistically significant, as very few experiments of this type have been performed. In any case, we would like to point out that integrated experiments are difficult to interpret using calculations. It is also uncertain why shots at very different adiabats are predicted to have the same DSR, and a near-consistent offset relative to data.

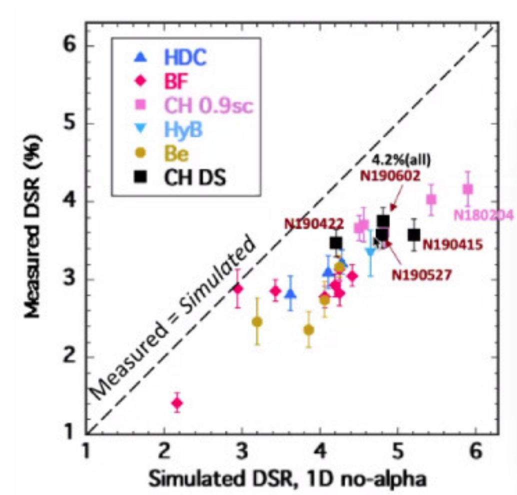

FIG. 5. The measured neutron downscattering ratio (DSR) vs. the simulated neutron downscattering ratio for NIF experiments. Note that simulated DSR is systematically higher than the measured value by a factor of 1.2 or more. (Courtesy of Dr. Denise Hinkel at NIF, LLNL [24].)

DSR is proportional to the total areal density of the capsule. We can use an analogy where the dynamics of an ignition capsule can be mimicked by the dynamics of a two-spring mechanical system with one end connected to a fixed wall as displayed in Fig. 6. In our analogy, the fixed wall is the center of the capsule. The inner spring (spring 1) is the hot spot and the outer spring (spring 2) represents the pusher. If a pusher is on a high adiabat, it is softer and less dense (i.e. low density), like a soft spring. When an external force presses the system, the majority of the work will go to the contact spring (spring 2, i.e., the pusher) and leaves the inner spring (hot spot) nearly uncompressed. Thus the total areal density of the

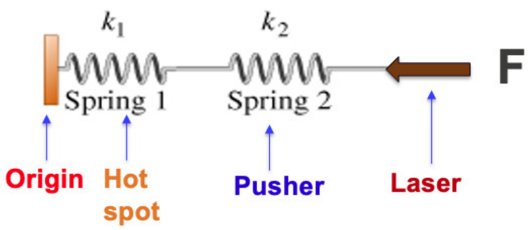

FIG. 6. An analogy of a two-spring system to a capsule consisting of pusher shell and hot spot. The fixed wall represents the center of the capsule. Inner Spring 1 represents the hot spot and the outer Spring 2 represents the pusher shell.

capsule will be low (low areal density in both pusher and hot spot). If the pusher is on a low adiabat, it would be stiffer and denser (i.e. high density). When an external force presses the system, the outer spring absorbs less work, most of the energy will go to the inner spring (i.e., spring 1). Thus, the inner spring will be pushed harder and the hot spot will be more compressed. Then the total areal density of the capsule will be high (high areal density in both pusher and hot spot).

Therefore, we conclude that when the pusher is at high density, more compression energy will go to the hot spot. Conversely, if the pusher is at low density, then more compression energy will stay in the pusher. The fact that the measured DSR has been persistently lower than the simulated DSR suggests that the pusher density in the simulations has always been higher than the real pusher density in the capsules tested, or in other words, the pusher adiabat in the simulations has always been lower than the real adiabat of the pusher in the capsules tested [26, 27]. This discrepancy has resulted in the constant overpredictions of the NIF capsule yields by preshot simulations [25]. Our analysis is in good agreement with the recent Be shots on NIF [41], in which a high pusher adiabat (due to mix or preheat) was purposely used in the preshot simulations and about 90% of the preshot predicted yield was achieved. The good agreement between theory and experimental data suggests that maintaining a high density pusher during the implosion can help to improve capsule performance.

5. PUSHER MASS

The capsule performance can be improved by increasing the peak implosion velocity as demonstrated in recent NIF experiments [42]. However, when the peak implosion velocity is increased past a certain point, the measured yield of the capsule drops off sharply. This phenomena is referred as the "velocity cliff" [43]. The existence of such a cliff is attributed to burn-through of the ablator, diminishing the confinement of the capsule and leading to increased mix in the pusher and/or potential x-ray preheat. As stated earlier, given an implosion kinetic energy ($M_p V_{imp}^2/2$), increasing peak implosion velocity comes at the cost of decreasing the pusher mass (M_p) and the remaining ablator mass. High resolution simulations [29] and recent Be experiments [40, 41] on NIF have shown that large interfacial instabilities would arise in case of low remaining ablator mass, then the shell would be easily burnt through and the pusher would be forced into a higher adiabat, which affects the energy partition between the pusher and the hot spot, leading to a low hot spot energy, areal density, and low neutron yield. This would help explains why a yield drop at high peak implosion velocity was observed in the recent NIF experiments. Therefore, in future designs, solely pursuing high implosion velocity without controlling adiabat and optimizing the pusher mass may not lead to the desired performance improvements.

Optimizing the pusher mass is important in capsule designs. Applying energy conservation law to capsule implosion from peak implosion velocity time to stagnation

$$\frac{1}{2}\eta M_p V_{imp}^2 = \epsilon_p M_p + \epsilon_{hs} M_{hs}, \tag{9}$$

shows the dual roles of the pusher: (1) as a carrier of the total energy into the capsule at the peak implosion velocity time, and (2) as an energy sink competing with the hot spot at the stagnation time. Where ϵ_p and ϵ_{hs} are, respectively, the specific internal energy of the pusher and the hot spot. Optimized pusher mass maximizes the hot spot energy and pressure with relationship [13, 15, 16] $P_{hs} = P_0[\gamma_p \eta_L \eta V_{imp}^2/((3\gamma_p - 1)\epsilon_0)]^{\frac{\gamma_p}{\gamma_p - 1}}$. Given observations at NIF, the pusher mass does not appear to be optimized as of yet. It has only been used to increase the peak implosion velocity, which results in a thin shell and an ultimately drop in yield if the implosion energy remains unchanged.

6. PUSHER TAMPING

Improving the tamping factor increases the fusion confinement time. Good tamping lowers the ignition threshold and increases hydrodynamic disassembly time and capsule yield. In the present NIF ice-layer design, tamping is minimal because the tamping factor is proportional to the square root of the mass density ratio of the pusher to the hot DT at the cold-hot DT boundary, i.e., $f_T \sim \sqrt{\rho_p/\rho_{hs}}$ [16, 44, 45]. Where ρ_p and ρ_{hs} are, respectively, the mass density of the pusher (cold DT) and the hot spot at the interface between the hot and cold fuel. During the DT burn in the hot spot, the cold DT fuel next to the hot spot is heated up, making the cold-hot fuel boundary smooth and continuous (not a step function) in density like a free boundary: the mass density of the cold fuel (ρ_p) is approximately equal to the mass density of the hot fuel at R_{hs}, so that $f_T \sim 1$. Therefore, the presence of an ice layer in the "pusher" actually reduces the tamping factor. If a robust TN burn propagation is not obtainable at a given laser energy, the ice layer in the point design is only an energy sink and may need to be removed. A relatively sharp gas-shell boundary would increase the tamping factor.

It is worthwhile to point out that an interface with a high density ratio may increase the interfacial instability between the pusher shell and the DT fuel because of the increased Atwood number [46, 47]. Also, removing the DT ice would directly expose the hot fuel to the inner edge of the higher-Z ablator, potentially enhancing mix. However, the instability and instability induced mix can be controlled by refining the inner surface, density and thickness of the pusher shell and by reshaping the pulse. Studies about the dependence of the mix width or extent on design variables is needed to help set the ice thickness. The benefits of increased tamping and energy into the hot fuel can far exceed the negative impacts from instabilities.

7. LASER ENERGY REQUIRED

Improving energy coupling in the capsule is crucial for ignition. Increased coupling efficiencies will increase the initial amount of DT fuel that can be imploded, which in turn will increase the hot spot mass, temperature, and pressure in an ignition capsule. Given a laser energy (E_L) and energy coupling coefficients (η_L and η), the maximum plausible hot spot mass that can be produced by the NIF energy is given by $M_{hs}^{maxp} \leq \eta_L \eta(\gamma_p - 1)(\gamma_g - 1) A_{DT} E_L / [(3\gamma_p - 1) 2RT]$, where R is the gas constant, T is the hot spot temperature, and E_L is in unit of MJ. If high Z material is part of the hot spot, then the effective maximum plausible hot DT mass would be $M_{hs}^{maxp*} = (1 - f_{mix}) M_{hs}^{maxp}$, where f_{max} represents the mass fraction of the high Z material in the hot DT.

Assuming a high pusher adiabat implosion, $\gamma_p = \gamma_g = 5/3$ and energy coefficient $\eta_L \eta \approx 1.6\%$ (estimated from the NIF experiments), for the upper limit of NIF energy, $E_L = 2$ MJ, taking $T = 5$ keV, we find $M_{hs}^{maxp} \leq 288 \eta_L \eta E_L \sim 9.2\ \mu$g, which is less than the required hot spot mass given in Table II for self-sustained TN burn that would lead to a robust burn propagation. However, if the TN burnup fraction of the hot spot could be $\sim 6\%$, then the 9 μg hot spot would be able to produce $\sim 7 \times 10^{16}$ fusion neutrons. The TN burnup fraction (or efficiency) of the hot spot is $\sim 2\%$ in shot N180128 and $< 1\%$ in most of the NIF shots.

The maximum plausible hot spot masses for various laser energy and pusher adiabat are displayed in Table II. This analysis reveals the great challenge or difficulty to produce the required hot DT mass (for example, 23μg at $T = 5$ keV and 40 μg at $T = 4$ keV for a convergence ratio of 27 as shown in Table I) for ignition by the present laser energy capacity or a modest upgrade ($\sim$ 3 MJ) of the present NIF if the energy coefficients η_L and η remain unchanged.

Energy (MJ)		M_{hs}^{maxp} (μg)	
Laser (MJ)	Peak KE (kJ)	High adiabat $\alpha = 3$	Low adiabat $\alpha = 1.5$
2.0	32	9.2	14
2.5	40	12	18
3.0	48	14	21

TABLE II. Maximum plausible hot spot masses for different laser energies, peak implosion kinetic energy (Peak KE), and pusher adiabat. The required hot spot mass for pure DT at $T = 5$ keV and $C_f = 27$ is 23 μg (see Table I) for comparison purposes.

Accordingly, we can estimate the minimum required laser energy (E_L^{min}) or the minimal peak implosion kinetic energy (E_{pk}^{min}) for achieving ignition on NIF given the present energy coupling efficiency, which is $E_L^{min} \geq 2RT(3\gamma_p - 1)M_{hs}/[A_{DT}\eta_L\eta(\gamma_p - 1)(\gamma_g - 1)] \simeq 7.23 \times 10^{-4}(3\gamma_p - 1)(M_{hs}/\mu g)(T/\text{keV})/(\gamma_p - 1)$ MJ [20] or $E_{pk}^{min} = \eta_L \eta E_L^{min}$, where $\eta_L \eta \approx 1.6\%$ has been used. Substituting the minimum required hotspot mass of 40 μg for ignition at $T = 4$ keV and convergence ratio of 27 in the expression, we obtain the minimum laser energy required $E_L^{min} \geq 4.7$ MJ or the minimum peak implosion kinetic energy $E_{pk}^{min} = 75$ kJ for ignition in a low pusher adiabat ($\alpha \sim 1.5$) and $E_L^{min} \geq 10$ MJ or $E_{pk}^{min} \geq 160$ kJ in a high pusher adiabat ($\alpha \sim 3$).

Similarly, to achieve ignition at T = 5 keV and a minimum hot spot mass of 23 μg at convergence ratio of 27, the required minimum laser energy or peak implosion kinetic energy are, respectively, $E_L^{min} = 3.5$ MJ and $E_{pk}^{min} = 56$ kJ at low adiabat ($\alpha \sim 1.5$) and $E_L^{min} = 7.5$ MJ and $E_{pk}^{min} = 120$ kJ at high adiabat ($\alpha \sim 3$). Maintaining low pusher adiabat implosion and high peak kinetic energy is essential in ignition capsule designs and reducing the amount of required implosion energy. However, preheat and fuel-ablator mix are the two current obstacles preventing the capsules being on a low adiabat. Thus, mitigation of preheat and fuel-ablator mix would be the top priority in ignition capsule design so as to increase the hot spot energy, mass and TN burn efficiency and substantially reduce the required drive energy.

8. CONCLUSION

We have presented the fundamental factors affecting the TN burn through the minimal energy implosion model. Our analysis shows that the present design of the NIF ignition capsules could be further improved and optimized to increase the capsule performance. Firstly, working with high adiabat using high density shell and a possible thin layer between the fuel and ablator would minimize the adiabat of the cold fuel and reduce the mix between the cold fuel and ablator. Secondly optimizing the pusher mass or thickness would increase and maximize the specific energy density ratio (the peak specific kinetic energy to the peak specific hot spot energy) and hot spot pressure; Thirdly, designing the capsules from inside-out instead of outside-in would address the physics requirements for the hot spot mass, energy and pressure. Before NIF achieves burn propagation and ignition, the ice layer of the fuel has been an energy sink to the capsule, removing the ice layer in the present design would optimize the tamping factor and the energy into the hot spot and, hence, increase the neutron yield but with no ignition. Finally we would like to point out that an upgrade of the NIF laser energy to 3 MJ may not be enough to lead to an ignition on NIF. An economic way to increase the implosion energy would be to use direct drive implosion on NIF [49]. However, the challenging issues associated with CBET have to be addressed if NIF moves to PDD configuration.

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