Overview of Progress and Future Prospects in Indirect Drive Implosions on the National Ignition Facility

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Abstract. Alpha-particle self-heating, the process of deuterium-tritium (DT) fusion reaction products depositing their kinetic energy locally within the fusion reaction region and thus increasing the temperature in the reacting region with a concomitant exponential increase in the fusion reaction-rate, is the essential process needed for a fusion plasma to ignite. For the first time in the laboratory, significant alpha-heating in a fusion plasma was inferred in experiments and fusion fuel gain was demonstrated on the U.S. National Ignition Facility (NIF). Experiments on the NIF have achieved the highest yet recorded stagnation pressures (P_{stagnation} > 150−230 Gigabar) of any facility based inertial confinement fusion (ICF) experiments, albeit they are still short of the pressures required for ignition on the NIF (i.e. ∼300−400 Gbar), and have exhibited undesirable shape distortions that waste kinetic energy. We review the issues that have been uncovered and discuss the program strategy and plan that we are following to systematically address the known issues as we press on.

1. Introduction
The physics basis for indirect drive ignition on the NIF has been documented previously [1, 2, 3] as was the subsequent outcome of the National Ignition Campaign (NIC) [4] - the three-year effort to achieve ignition from 2009 to 2012. The NIC implosion focused upon a design that emphasized maximizing fuel $\rho R$ for the purpose of minimizing the energy required for ignition while achieving high gain. In this paper, we concentrate on the status and prospects based upon the last few years of post-NIC progress and scientific exploration on the NIF that leverage the remarkable diagnostic suite developed under the NIC aegis.

2. Progress since 2012
Since 2012, progress has been made towards ignition conditions (see Fig. 1) by using pulse shapes that are resistant to hydrodynamic instabilities [such as the ablative Rayleigh-Taylor (A-RT) instability] over a range of ablator materials, pulse-shapes, and hohlraum gas-fills. In a strategy of performing implosions that are less stressing of the physics by using laser pulse-shapes that mitigate the ablative Rayleigh-Taylor instability, reducing capsule convergence ratios, and making small systematic steps in a complex parameter space of initial conditions, notable accomplishments have been: (1) Fusion fuel-gain $G_{fuel} > 1$ with significant alpha-particle self-heating [5] (not to be confused with ‘ignition’ or ‘target gain’); (2) Demonstrating stagnation pressures in excess of 200 Gbar [6, 7] at temperatures of about 5 keV; (3) Achieving more than a...
Figure 1. The classical Lawson Confinement parameter, $P_{\tau}$, is plotted against ion temperature, $T_{\text{ion}}$, for the various implosion campaigns on the NIF. The NIC low-foot implosion shots are shown in blue, the high-foot implosion shots are shown in green, the adiabat-shaping shots (both 3-shock and 4-shock) are shown in magenta, the near-vacuum hohlraum high-density-carbon (HDC) shots are shown in yellow, the high-gas-fill hohlraum HDC shots are shown in orange, and the one beryllium ablator shot to date is shown in grey.

doubling of the fusion yield due to alpha-particle self-heating with fusion yields of 26 kJ[6, 7, 8, 9];
(4) Demonstrated mitigation of the ablative Rayleigh-Taylor instability via laser pulse-shape modifications [10, 11, 12, 13, 14] in a way that was consistent with theoretical expectations [15, 16, 17]; (5) Demonstration of DT implosions that range in levels of fuel compression from $\rho R = 0.6 \text{ g/cm}^2$ to $\rho R = 1.1 \text{ g/cm}^2$ [18, 19, 20, 21, 22, 23, 24, 25] with fuel velocities in excess of 380 km/s [6, 7, 26] with no indications of mixing of ablator material into the hot-spot.

However, in the process of obtaining the above results a significant body of the data imply that the higher convergence and higher velocity indirectly-driven implosions of the NIF are not behaving like the ideal “text-book” [1, 27] implosion in spite of mitigating the growth of hydrodynamic instabilities. This deviation from ideal behavior was not entirely unexpected, since numerous issues were suspected in degrading the performance of NIC implosions, and mitigating the A-RT only addressed one (dominant) issue. These newer A-RT mitigated and less stressful implosions on NIF serve as integrated diagnostics of the remaining difficulties.

2.1. High-foot Implosions

As was documented in a series of experiments that incrementally increased laser drive (Fig. 2) on high-foot implosions [18, 19], symmetry of the implosions’ central hot-spot degraded as laser-power was increased in hohlraums with 1.6 mg/cm$^3$ of helium gas fill, resulting in oblate and sometimes even toroidal hot-spots. Increasing laser energy, instead of laser power, appeared to be preferable in terms of hot-spot symmetry control and net fusion performance, in contradiction to the conventionally expected behavior. A key element of managing implosion symmetry in the high gas-fill hohlraum was a reliance upon manipulating cross-beam energy transfer (CBET). This laser-plasma instability was used to force more energy onto the middle circumference of
High-foot DT implosion shots are plotted for three different ablator thicknesses: 195 µm ("T0," green), 175 µm ("T-1," cyan), and 165 µm ("T-1.5," magenta). Inset is the measured ablator optical depth inferred from the south-pole-bang-time (SPBT) x-ray diagnostic. The 165 µm shot that appeared to break the observed scaling of yield vs. laser energy (which is proportional to capsule absorbed kinetic energy) has little optical depth along the southern line-of-sight. The increase in yield observed in the plot at fixed laser energy is a result of switch the hohlraum material from pure gold (Au) to Au-lined depleted uranium (U). Inferred stagnation pressure for the high-foot series vs. coast-time (the time difference between bang-time and the time the laser is turned off). Interestingly, small changes in coast-time (∼100’s of ps) result in large changes in stagnation pressure (and yield). At very short coast-times (< 500 ps), the stagnation pressure appears to drop (albeit the number of data in that region is small). Very little ablator material remains for implosions with very small coast-times, placing the implosion at risk for burn-through or loss-of-confinement through thin-spots in the ablator.

Further improvements in hot-spot symmetry control and net fusion performance were obtained by transitioning from a gold (Au) to depleted uranium (DU) hohlraum [7]. For a fixed amount of laser drive, DU effectively increases the peak hohlraum radiation temperature, $T_r$, and therefore ablation pressure. DU atomic physics differences also increase the emissivity at the hohlraum waist thereby driving the waist of the implosion slightly harder than in Au, and reducing the tendency towards oblate implosions. To a limit, reducing ablator thickness was also effective at improved symmetry control and net fusion performance [26]. Thinner ablators, while risking more instability because of increased in-flight-aspect-ratio, obtain higher implosion speed for a given peak $T_r$, and also inject less ablator plasma into the hohlraum thereby facilitating the propagation of the laser beams. While fusion yields and stagnation pressures increased as the implosion velocity was increased and reproducibility of nuclear performance was demonstrated [26], eventually a performance maximum and cliff were identified [6]. The observed performance cliff showed no evidence of hot-spot mix, but low measured optical depth along at least one diagnostic line-of-sight (Fig. 2), suggested thin-spots in the shell of the implosion that resulted in a loss of confinement [8].

Integrated two-dimensional (2D) post-shot simulations of the high-foot target series [32] and three-dimensional (3D) simulations [33] are largely self-consistent with data and imply that implosion asymmetry is a key mechanism responsible for the measured fusion performance of the hohlraum [28, 29, 30, 31], but there are limits to this technique as there are limits to the maximum amount of energy the laser itself can supply. Moreover, even after years of using CBET, to successfully manage gross aspects of implosion symmetry, considerable uncertainty exists surrounding the detailed time-dependence of the energy transfer.
Time-integrated x-ray emission imaging data shows a variety of hot-spot morphologies for a sample of different NIF implosions (from left-to-right the beryllium DT implosion, one of the highest yield and stagnation pressure high-foot implosions, the highest fuel $\rho R$ adiabat-shaped implosion, and the highest yielding near-vacuum HDC implosion. The top row is the equatorial view of the implosion hot-spot and the middle row is the polar view of the implosion hot-spot. Similar shapes are seen in time-resolved x-ray emission data and in neutron imaging data (neither of which are shown here). Indirectly, the flange neutron activation data (FNAD) gives some reflection of the shell of DT fuel $\rho R$ distribution. Even in cases where the hot-spot emission appears round (and it usually isn’t), the FNAD’s indicates large deviations from a 1D implosion in the confining shell – this is a problem.

High-foot targets, but not the only mechanism (the tent and 3D features seem to be of increasing importance for the high-velocity high-foot experiments). Additionally, while mitigating A-RT reduces the damage to the implosion coming from the tent mounting membrane, data indicate the hot-spot [34] and shell [35] of the high-foot implosions are still impacted. Hot-electrons, generated in the plastic window plasma at the “laser-entrance-holes” (LEH’s) [36, 37] are another potential source of asymmetry. Regardless of their origin, asymmetries degrade the conversion of kinetic energy of the imploding fuel shell into internal energy upon stagnation [32, 38] and, if severe enough, can lead to a loss of confinement through thin-spots that develop in the fuel and remaining ablator. Data and post-shot simulations indicate that, presently, many indirectly driven NIF implosions have poor shell symmetry [39, 40, 41] even when the hot-spot appears fairly round regardless of ablator or pulse-shape (Fig. 3).

### 2.2. Alternate Ablator Materials and Adiabat-Shaping

Remarkably, experiments using alternate and more efficient ablator materials such as beryllium (Be) [42, 43, 44] or high-density-carbon (HDC, i.e. diamond) [22] had the same essential fusion performance as CH ablators when driven by the same gas-filled hohlraum and high-foot pulse-shape (Fig. 4), even having the same observed hot-spot shape in the case of HDC [25]. Results which imply that the gas-filled hohlraum is dominating the performance of these implosions.

Attempts at retaining the good hydrodynamic stability properties of the high-foot targets, while returning to the higher levels of compression of the NIC implosion via adiabat-shaping [17, 45, 46], were successful in increasing the fuel $\rho R$ by $\sim 20\%$ from where the high-foot fuel $\rho R$ saturated in a high gas-fill hohlraum [20, 21, 47] and in greatly reducing the signatures of hot-electrons effusing from the hohlraum (at 350 TW and 1.6 MJ of laser power and energy). However, the fusion yield performance and inferred stagnation pressure were essentially not improved as compared to high-foot implosions with equivalent target geometry and laser drive (Fig. 4). These results suggest that the dense fuel-shell and central hot-spot properties are not as coupled as one would expect for a uniform 1D implosion. At higher laser drive (388 TW...
and 1.74 MJ) and with a thinner (175 μm) ablator, the total neutron yield and fuel \( \rho R \) were comparable, to within error bars, for adiabat-shaped and equivalently driven high-foot shots \[48\], perhaps as a result of late-time hot-electron preheat at high drive.

2.3. Improved Hohlraums and Engineering Features

Larger case-to-capsule ratio (the ratio of inner hohlraum wall and outer capsule radii) near-vacuum hohlraums, which are well suited to the very short laser-pulse durations of the HDC ablator, have shown \( \sim 98\% \) levels of laser-to-hohlraum energy coupling, the ability to control symmetry directly through laser cone-fraction without needing CBET, and levels of hot-electrons \( 100 - 1000 \times \) less (over an energy range of 50-300 keV) \[23, 24\]. The addition of a small amount of helium gas (0.3 - 0.6 mg/cc), for a low gas-fill hohlraum configuration, makes it possible to utilize less efficient ablators such as CH yet retain much of the benefit of the near-vacuum hohlraum \[49\] – a direction which indirect-drive work on NIF is just now developing to address the obstacle of implosion shape control. Work on alternate geometry hohlraums (e.g. the “rugby”), which have also demonstrated low hot-electron levels is also ongoing in tight collaboration with CEA in France \[50\].

3. Conclusions

Work to clearly assess and mitigate the negative impact of engineering features in contact with the capsule is also just developing. Once the major challenges of implosion time-dependent shape control and capsule mounting features are addressed, it is anticipated that other challenges will emerge from the data. Progress will be made towards ignition by systematically addressing each challenge uncovered in a disciplined series of steps, getting into the burning plasma regime next, in order to better master implosion finesse. Experiments that back away from highly stressing (e.g. high convergence ratio) implosions will be pursued to assess where numerical simulations depart from observation in order to determine what improvements are needed in our predictive capability. In parallel, efforts focusing upon delivering more energy to the imploding DT fuel, which lessens the need for high finesse, will also be developed.
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