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The Ignition Physics Campaign on NIF: Status and Progress

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Significant progress has been made in ICF implosions on NIF. In these experiments ~ 1.8MJ of laser light is delivered to a ~ 1cm long cylindrical hohlraum, which generates x-rays to implode a ~ 2mm diameter plastic capsule containing a deuterium-tritium (DT) fuel mixture. To date total DT fusion neutron yields have increased to ~ 26 kJ (9.3 $x10^{15}$ neutrons), which is less than the 1.8MJ delivered by the laser but greater than the ~ 12kJ of energy invested in the DT fuel during the implosion. Most significantly, for the first time in the laboratory the yield is doubled as a result of self-heating by ^{4}He particles, a byproduct of the DT fusion reaction. This talk will describe recent progress, remaining challenges and paths being pursued in an attempt to overcome them.

1. Introduction

A primary goal of the Inertial Confinement Fusion (ICF) program on the National Ignition Facility (NIF) is to implode a spherical capsule filled with a cryogenic deuterium-tritium (DT) fuel layer via laser indirect-drive and demonstrate fusion ignition and propagating thermonuclear burn. At the end of the National Ignition Campaign (NIC) in 2012, we had demonstrated implosion parameters at ~ 80-90% of most ignition point design values, though not simultaneously. In low-mix implosions the nuclear yield was a factor of ~ 3–10X below the simulated values and a similar factor below the alpha-dominated regime. The principal reason for this appeared to be a hot spot density and pressure that was factor of ~ 2-3 below the simulated values. Ablator mix into the hot spot was observed at lower velocities than predicted and correlated strongly with the measured ion temperature and yield. Indications were that this mix was being driven by hydrodynamic instability at the ablation front. Several diagnostic measurements—both in-flight and at fuel stagnation—revealed time-dependent low-mode shape asymmetries in the ablator and cold fuel which may explain some of the deficit in pressure and the larger than expected mix. In order to achieve the required symmetric capsule shape, we typically transfer a large fraction (~ 30%) of the energy and power from the outer to the inner beams via Cross-Beam Energy Transfer (CBET). Since this transfer is dependent on the laser intensity and the plasma conditions in the region of the overlapping beams, it is not well modeled yet in an integrated fashion in the simulation codes. We believe the time and spatially varying CBET is to a large extent responsible for observed time dependent asymmetries of the imploded capsule and contributed to the decrease in implosion performance as the laser power and capsule implosion velocity were increased. During 2013-14, the theoretical and experimental effort has been focused on understanding the underlying physics issues responsible for the deviation from modeled performance, with particular emphasis on the areas of low-mode shape asymmetry and mix.

2. Low Mode Shape

One route to minimizing the effect of CBET, and hence improve time-dependent shape, is to reduce or eliminate the need for a hohlraum gas fill by employing shorter duration laser pulses. This is challenging with the traditional 4-shock CH ablator design, but can be more easily achieved with the use of higher density ablators such as high-density carbon (HDC) and by reducing the number of shocks to 2 or 3. HDC is an interesting option as an ablator material for indirect drive ICF implosions. Its higher density than plastic (3.5 g/cc vs. 1 g/cc) results in a thinner ablator with a larger inner radius for a given capsule scale. It exhibits higher x-ray absorption and higher overall efficiency, with a shorter laser pulse, than equivalent CH designs. During 2013-14, we carried out a series of experiments to examine the feasibility of using HDC as an ablator with 2, 3, and 4-shock laser pulse designs.

A 2-shock high-adiabat (α ~3.5) design using an un-doped HDC capsule was developed to reduce the ablation front growth factors by more than a factor of 10 over the ignition-scale 4-shock HDC design. This 2-shock pulse is not an ignition design but it is predicted to produce ~ 2E16 yield in 1-D, which would allow valuable insight into implosion performance in the alpha-heating regime. The 6-7 ns pulse allows less time for wall motion and plasma filling and opens up the possibility of using hohlraums with very low gas fill (He density ~ 0.03 mg/cm^3), or near-vacuum hohlraums. Advantages of near-vacuum hohlraums, in addition to minimizing CBET, are reduced backscatter, little or no hot electron generation, and very high (98-99%) hohlraum efficiency. A campaign was conducted to explore the performance of the 2-shock HDC design, culminating with a 1.16 MJ, 305 TW shot with a cryogenic DT-layered target that produced 1.8E15 neutrons. Laser-to-hohlraum coupling was 98.5%, and post-shot simulations indicate yield-over-simulated performance of ~ 25-50%. An earlier cryogenic THD layered implosion version was consistent with a fuel velocity = 430 ±50km/s with no observed ablator mixing into the hot spot.

3. High Foot Design

The goal of the 'High-foot' campaign was to manipulate the drive to create a more one-dimensional and robust implosion that is more resistant to ablation driven hydrodynamic instabilities and the resulting mix of the ablator into the DT fuel. The high foot CH design uses the same target as the low foot NIC design. The key pulse-shape changes, as compared to the low-foot pulse, are more laser power at early time, which causes the radiation temperature in the 'foot' of the pulse to be higher, and 3 shocks instead of 4. The higher foot temperature and resulting higher adiabat causes more ablative stabilization, longer scale lengths and lower In-Flight-Aspect-Ratio (IFAR). However it also results in lower final density, reducing ideal margin for ignition in 1-D.

A series of DT-layered high-foot implosions were carried out in 2013-14. They had high yield-over-simulated performance (50-70%) and have been diagnosed to have very low mix. As of September 2014, the highest DT yield obtained is 9.3E15 neutrons, or 26 kJ of fusion energy, a factor of 10X increase over the previous highest performing low-foot shot. At this yield 5.2 kJ is released in alpha-particle kinetic energy. Most of the alpha particles are stopped in the hot spot and contribute to additional self-heating, which further boosts the hot spot energy and neutron yield. For this shot we estimate that the total yield was more than doubled due to the effect of self-heating. We are thus entering the regime where alpha-heating increasingly dominates the hydrodynamics and energy balance in the hot spot. The inferred levels of CH ablator mix into the hot-spots were low for the high-foot implosions, confirming the reduction of ablator mix for the high-foot design. As with the low-foot NIC targets, the high-foot hohlraums also required large CBET in order to achieve adequate hot-spot symmetry. Further increasing the yields will require increasing the implosion velocity and compression, as well as improving the hohlraum drive symmetry. Using Rugby shaped holraums we have demonstrated uniform x-ray drive with minimal Cross Beam Energy Transfer (CBET), and we plan to use these hohlraums in upcoming High Foot experiments.

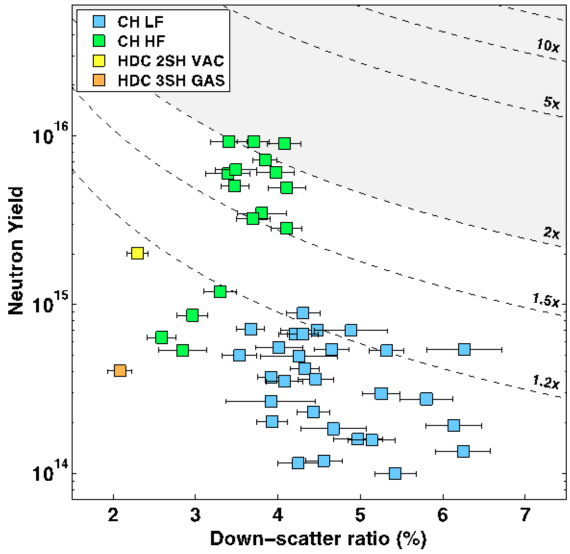

Fig.1. Neutron yield plotted against down-scatter ratio (DSR)—the ratio of down-scattered to unscattered neutrons. DSR is approximately proportional to the DT fuel ρR. Dashed lines are contours of yield amplification—the factor by which the yield is predicted to increase due to alpha-particle self-heating. High foot CH targets using a 3-shock design [green] have demonstrated a total neutron yield of 9.3E15, representing a 10-fold increase over the low-foot CH design [blue]. A DT-layered HDC target with a 7 ns, 2-shock pulse in a near vacuum hohlraum have achieved a yield of 1.8E15 [yellow].