The Ignition Physics Campaign on NIF: Status and Progress

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Abstract. We have made significant progress in ICF implosion performance on NIF since the 2011 IFSA. Employing a 3-shock, high adiabat CH ("High-Foot") design, total neutron yields have increased 10-fold to 6.3 $x10^{15}$ (a yield of ~ 17 kJ, which is greater than the energy invested in the DT fuel ~ 12kJ). At that level, the yield from alpha self-heating is essentially equivalent to the compression yield, indicating that we are close to the alpha self-heating regime. Low adiabat, 4-shock High Density Carbon (HDC) capsules have been imploded in conventional gas-filled hohlraums, and employing a 6 ns, 2-shock pulse, HDC capsules were imploded in near-vacuum hohlraums with overall coupling ~ 98%. Both the 4- and 2-shock HDC capsules had very low mix and high yield over simulated performance. Rugby holraums have demonstrated uniform x-ray drive with minimal Cross Beam Energy Transfer (CBET), and we have made good progress in measuring and modelling growth of ablation front hydro instabilities.

1. Introduction.

A primary goal of the Inertial Confinement Fusion (ICF) program on the National Ignition Facility (NIF) is to implode a low-Z capsule filled with ~ 0.2 mg of DT via laser indirect-drive ICF and demonstrate fusion ignition and propagating thermonuclear burn [1].

At the end of the National Ignition Campaign (NIC) in 2012, we had demonstrated implosion and compressed fuel conditions at ~ 80-90% for most ignition point design values independently, but not at the same time [1]. For 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 therefore pressure, that was factor of ~ 2-3 below the simulated values, although the stagnation pressure scaled with implosion velocity as expected. Ablator mix into the hot spot was also 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. Angular measurements of down-scattered neutrons indicate that there could be low spatial mode asymmetries in the compressed main fuel, which may explain some of the deficit in pressure and the larger than expected mix. The NIC target is shown in Fig. 1.

In order to achieve the required symmetric capsule shape, we typically have to transfer a large fraction (~ 30%) of the energy and power from the outer to the inner beams via Cross-Beam Energy Transfer (CBET) [2, 3]. 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 increased [3, 4].

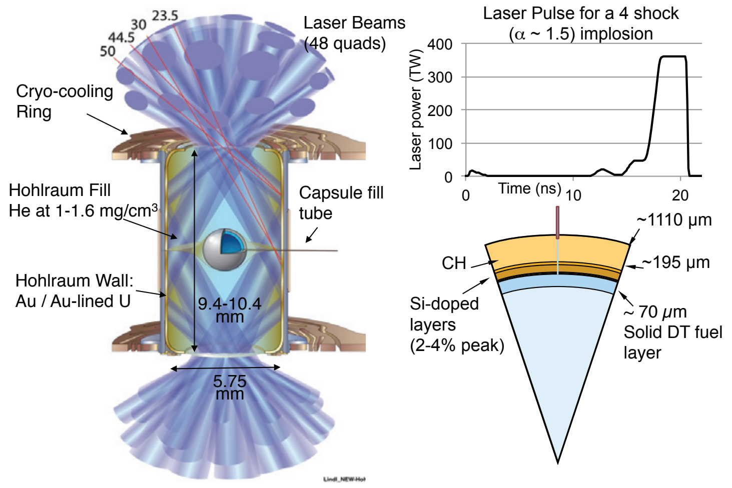

Fig 1. Schematic of NIF CH capsule in a gas-filled Au or Au-lined U hohlraum and a typical laser pulse that produces a 4-shock low adiabat (α ~1.5[1]) implosion. The laser power is stepped in time to gradually increase the X-ray drive on the capsule such that the pressure in the ice is increased in four shocks from ~1 Mbar to a value in excess of 100 Mbar during the implosion phase. The hohlraum is filled with He gas at a density ~ 0.96 mg/cm^3, to control wall motion for drive symmetry control.

During 2013, the theoretical and experimental effort has been focused on understanding the underlying physics issues responsible for the deviation from modeled performance. This paper provides an overview of the current progress of the X-ray drive ICF program, and in particular discusses the results of 1) implosions of CH capsules under drive conditions that are more robust to hydrodynamic mix; 2) preliminary results of implosions in Rugby-shaped hohlraums with minimal CBET; and 3) implosions with High Density Carbon (HDC) ablators both in gas-filled and Near Vacuum Hohlraums (NVH). He gas fill in NVH has so far been 0.03 mg/cm^3.

2. Higher Adiabat, High Foot, Lower Hydrogrowth Implosions with CH Capsules.

The goal of the 'High-Foot' campaign is to manipulate the laser pulse-shape and the resulting drive (see Fig.2) 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 [5-8]. 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 (hence the name 'High-Foot'), 3 shocks instead of 4 and a decrease in pulse length to maintain shock timing. The drive for the High-Foot capsule is tailored to control the ablation front instability growth. 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.

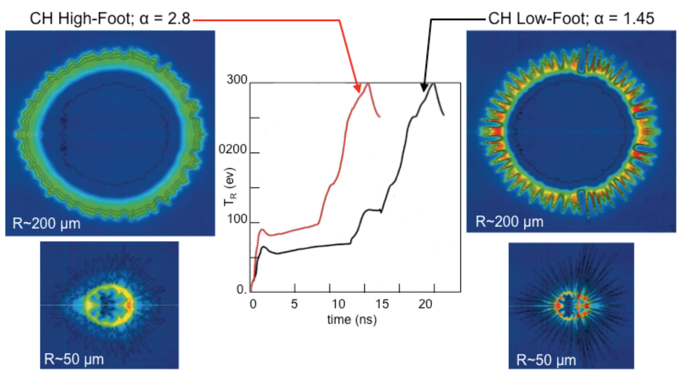

Fig. 2 Simulations of high and low-foot implosions at two different radii. The higher foot implosions show less fine-scale structure, indicating resistance to acceleration driven instability, and lower ablator density, indicating less compression. The values of alpha shown at top are the adiabat of each implosion. The 3-shock and 4-shock radiation drives for high and low foot is shown in the center.

The reduction of growth of surface perturbations for the high foot implosions was measured in a series of hydro-growth experiments (see Fig. 3) [9, 10].

[1] Adiabat defined as P/P_{cold}, where P_{cold} is minimum pressure at 1000g/cc from EOS of DT [17].

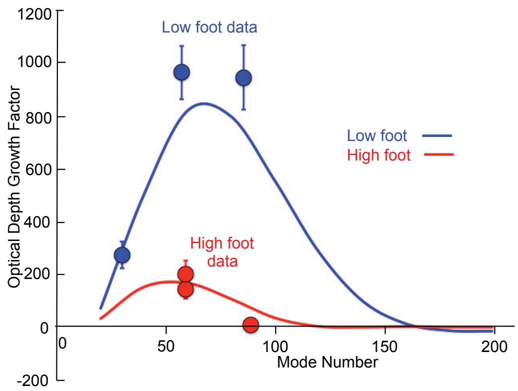

Fig. 3. Pre-imposed capsule surface perturbations with several different modes were probed using both the low and high foot pulse shapes. Linear growth factor is shown as a function of mode number for both low and high foot drive at the time the shell has converged to 650 μm and demonstrates reduced growth for mode 60 and significantly reduced growth of mode 90 when comparing high foot to low foot drive, as was expected due to its higher adiabat design. Simulations for growth are seen to be in reasonable agreement with the data.

A series of DT-layered high foot implosions were carried out in 2013 (see Fig. 4). They had high yield-over-simulated performance (50-70%) and have been diagnosed to have very low mix. By the end of November 2013, total DT neutron yields of 6.3 x10^{15} (a yield of ~ 17 kJ) were obtained. In the highest yield shot (N131119 in Fig. 4) the yield from alpha self heating is essentially equivalent to the compression yield, meaning that NIF results are very close to alpha dominated performance. As with the low-foot NIC targets, the high-foot hohlraums also required large CBET in order to achieve adequate hot-spot symmetry [5-8]. As can be seen from the time integrated hot-spot polar and equatorial x-ray images of Fig. 4, and the corresponding equatorial neutron images in Fig. 5, achieving symmetry and high velocity at the same time remains a challenge, even for the high foot design.

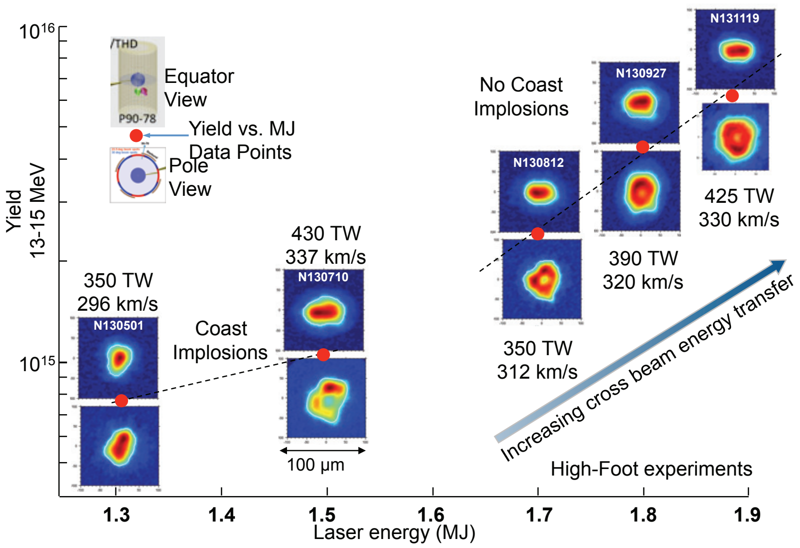

Fig. 4. Total neutron yield and time integrated hot-spot polar and equatorial images as a function of laser energy in MJ for the DT layered high-foot shots. Early experiments with 1.3-1.5 MJ were "coast" implosions, where the laser pulse was turned off when the ablator/fuel interface was at a radius of 600 μm. In order to increase the implosion velocity and prevent shell decompression, later "no-coast" experiments had a longer peak power pulse (and correspondingly larger total laser energy).

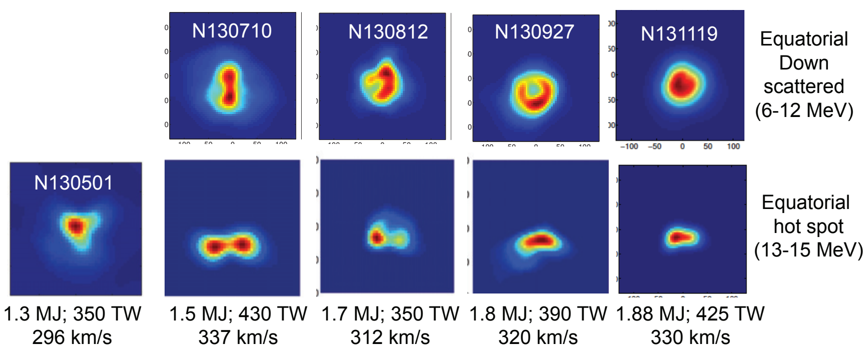

Fig. 5. Neutron images [11-13] for shots of Fig. 4. The upper row shows images of the down-scattered neutron from the high-density main fuel and the bottom row has images of the hot spots produced by the 13-15 MeV neutrons.

In spite of the toroidal shapes of the high-density main fuel and the asymmetric hot spots, 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. Further increasing the yields will require increasing the implosion velocity (v_{imp}) and compression, as well as improving the hohlraum drive symmetry. Near term we will attempt to increase v_{imp} by increasing laser energy and power, using thinner ablators as well as hohlraums made from Depleted Uranium (DU), and further fine tuning the CBET. Longer term, a more predictable, more efficient gas-filled hohlraum with better symmetry control is clearly desirable. Alternate ablators designs may also present more favorable conditions than the current experiments. This will be discussed in the next two sections.

3. Implosions in Rugby-Shaped Hohlraums.

Rugby-shaped gold hohlraums driven by low-adiabat laser pulse shapes have recently been tested on NIF [14]. The potential benefits of a rugby-shaped hohlraum (see Fig. 6) over the NIC-style cylindrical hohlraum (Fig. 1) can be exercised in two ways. The reduction in surface area over a NIC hohlraum with similar diameter and length results in a higher coupling efficiency and achieves a near 20% improvement in peak drive x-ray flux. Alternatively, a rugby hohlraum with a similar area to a NIC hohlraum will achieve a similar drive but due to the larger diameter, will have improved beam clearances (to the capsule and laser entrance holes) and higher hohlraum case-to-capsule ratio (CCR) for greater smoothing of hohlraum radiation modes, and could potentially allow uniform x-ray drive symmetry with minimal CBET.

The rugby hohlraum experiments on NIF tested the 2nd option. With a diameter of 7mm and a length of 10.5 mm the rugby has essentially the same surface area (to within a few %) as the current NIC hohlraum shown in Fig. 1. This results in a 22% larger CCR and nearly 30% greater beam clearance over the capsule than the NIC hohlraum. Simulations indicated that the rugby could have good inner beam propagation and x-ray drive symmetry without the large amount of CBET required to achieve adequate inner beam propagation and x-ray drive symmetry for the NIC hohlraum. For the NIC hohlraums an ~ 8Å wavelength separation between the outer and inner laser beams is used to transfer ~ 30% of the outer beam energy and power to the inner beams [3, 4].

The 7 mm rugby with a CH Symcap was fielded in May of 2013 with laser energy of 1.3 MJ and peak power of 370 TW. A 1Å separation between inner and outer beams was used, resulting in minimal CBET. The overall coupling was higher (~93% vs ~ 85%) than is typical for NIC hohlraums, and stimulated Raman scattering (SRS) backscatter from inner beams as a fraction of total energy was ~ ½ that observed for NIC hohlraums. However, the time integrated equatorial hot spot x-ray image was severely oblate with a P2/p0 of ~ 66% (see Fig. 6). Post-shot analysis done both by LLNL [14] and at the French CEA-DAM-DIF laboratory [15] indicated that Au plasma blow off from the hohlraum wall generated by the outer beams severely impeded the propagation of the inner beams.

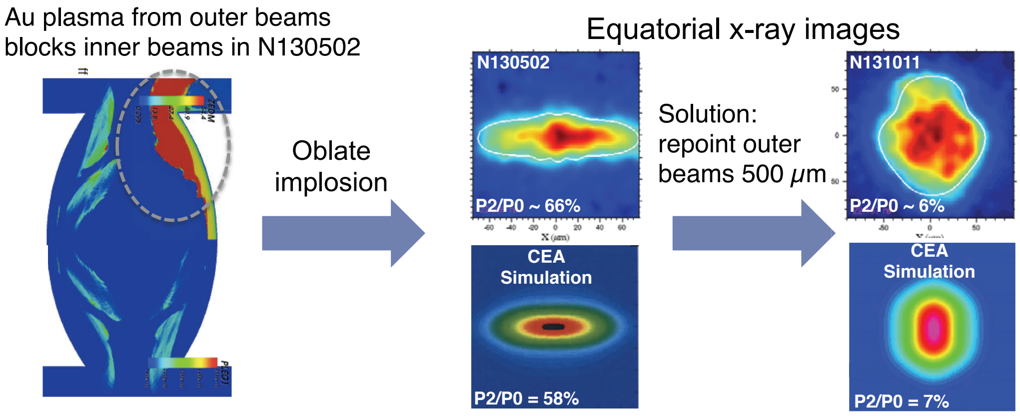

Fig. 6. Rugby target geometry and equatorial x-ray images from two NIF Rugby experiments. Also shown are simulated images generated by CEA-DAM-DIF.

The same post-shot simulations indicated that repointing the outer beams (moving the outer beams in by 500 μm) would eliminate the Au blow-off problem. The result from executing this repointing is also shown in Fig. 6. The laser energy and power were identical to the May shot and the same 1Å wavelength separation between inner and outer beams was used. Additionally, a small amount of Ne (2.5%) was added to the hohlraum gas fill in an attempt to reduce SRS, hot electrons generated by SRS, and 2-plasma decay. The primary objective of controlling core shape was successful and can be seen in Fig. 6. The central core emission was very close to round with a P_2/P_0 = 6% ± 1%. Additionally, a very low P_2/P_0 x-ray flux symmetry swing in time (< 10% P_2/P_0 per ns) was observed, in contrast to symmetry swings of ~ 30%/ns for NIC hohlraums that employ large CBET. The secondary objective of reducing SRS was marginally successful. The total measured SRS was similar to the May shot, but the hot electron signal, believed to be generated by SRS, was reduced by a factor of 4 or greater at all energies. There was also an increase in stimulated Brillion scattering which resulted in an overall coupling of ~ 88%.

It thus appears that a rugby hohlraum can indeed provide good x-ray drive symmetry with minimal CBET and offers the potential for low x-ray flux symmetry swings in time. Future high-foot experiments will take advantage of these features to increase v_{imp} and capsule implosion symmetry.

4. Implosions with High Density Carbon Ablators.

High Density Carbon (HDC) is an interesting option as an ablator material for indirect drive ICF implosions. HDC has a higher density (3.5 g/cc) than plastic (CH ~ 1g/cc), which results in a thinner ablator with a larger inner radius for a given capsule scale. This results in more pdV work done on a larger fuel and hot-spot volume and the thinner shell leads to less absolute inward motion during shock compression. The overall result is higher x-ray absorption (and higher overall efficiency) and shorter laser pulses compared to equivalent CH designs [16, 17] (see Fig. 7 and 8). During 2013, we carried out a series of experiments to examine the feasibility of using HDC as an ablator using both gas filled hohlraums and lower density, Near Vacuum Hohlraums (NVH)[16].

A series of five experiments using a 4-shock pulse shape designed to produce an adiabat 1.5 implosion culminated in a cryogenic CH symcap target filled with DT gas [18]. Fig.7 compares the HDC capsule and its 1.3 MJ, 350 TW laser pulse shape to a CH target and the low-foot pulse used for the adiabat 1.4 CH NIC implosions. With the slightly higher picket and foot for the HDC design, the He gas fill in hohlraum was increased to 1.2 mg/cm^3. The measured laser to hohlraum coupling for N130628 was 91 ± 2%, compared to 87 ±3% average for gas filled hohlraums driving CH capsules [19]. The DT neutron yield of 1.6x10^{15} at an ion temperature of 2.9 ± 0.1 keV is the highest gas-filled implosion yield to date and had a better than 50% Yield-over-Clean (YoC).

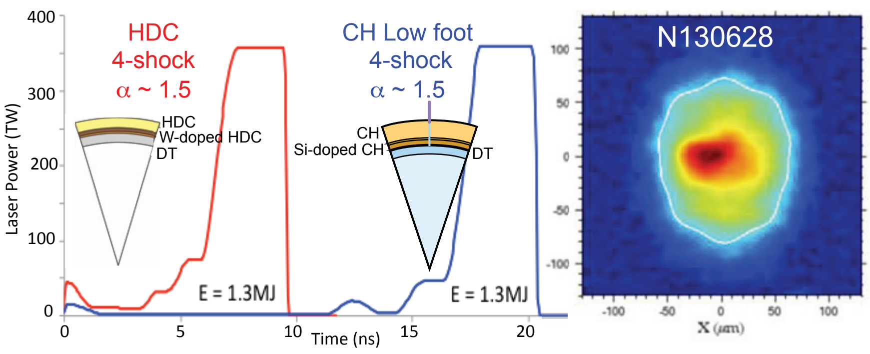

Fig. 7a The 4-shock, 1.5 adiabat laser pulse for HDC is 50% shorter than the 4-shock low foot 1.5 adiabat laser pulse for the NIC point design CH target.
Fig. 7b Time integrated x-ray image of hot spot is fairly symmetric with an average radius 57±4 μm and a P2/P0 = 0.19 ± 0.08

In addition to the 4-shock HDC design discussed above, there are also HDC designs with 2 and 3 steps (or shocks) in the x-ray drive [16]. These are compared in Fig. 9 with the 3-shock CH high-foot and the 4-shock NIC low foot, low adiabat CH designs.

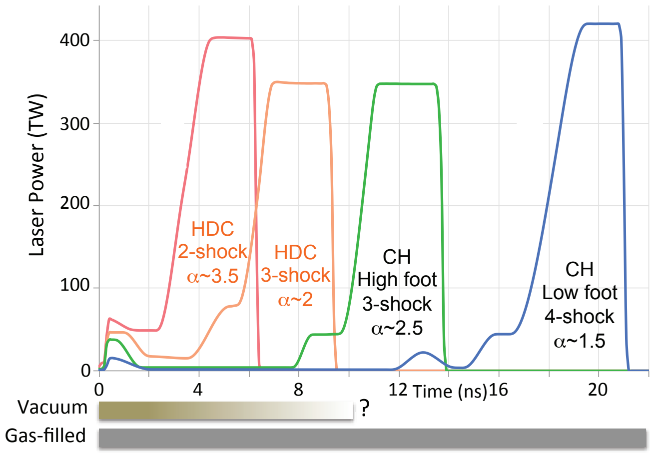

Fig. 9. Pulse shapes and adiabats for 2- and 3-shock HDC, and high and low foot CH designs. The bars below the plot indicates that although gas-filled hohlraums can be used for all designs, (and must be used for the 14-22 ns pulse length required for CH targets), the pulse lengths for the 2- and 3-shock HDC implosions are short enough that near vacuum hohlraums can (and have been) used for the 2-shock HDC design, and possibly could be used for the 3-shock design.

The 2-shock high adiabat (α ~3.5) design uses an un-doped HDC capsule to reduce the ablation front growth factors by more than a factor of 10 over the 4-shock HDC design. This 2-shock pulse is not an ignition design but it is predicted to produce ~ $2x10^{16}$ yield in 1D, which would allow valuable insight into implosion performance in the alpha heating regime while minimizing the effect of ablation front instability growth. 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 = $0.03mg/cm^3$), or Near Vacuum Hohlraums (NVH). The advantage of a NVH is that it has reduced backscatter, little or no hot electron generation and very high (98-99%) hohlraum efficiency [20]. A series of shots were conducted to explore the performance of the 2-shock HDC design in a NVH [16], culminating with a 1.16 MJ, 305 TW shot on a cryogenic DT-layered shot that produced $1.8x10^{15}$ neutrons (see Fig. 10). 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. The remaining issue with these types of hohlraums is that plasma filling in large laser spot motion. In particular, the inner beams provide the x-ray drive to the capsule equator and impaired propagation leads to asymmetry and/or time dependent symmetry swings through the peak of the x-ray drive. Future plans include the use of larger diameter cylindrical and/or shaped hohlraums to mitigate this effect.

HDC ablators have been shown to perform well in ICF implosions using both conventional gas filled and NVH. NVH may provide an alternate path for higher adiabat implosions with very high velocities and little or no hotspot mix. These high velocities, in excess of 370km/s and the high hohlraum efficiency (>98%) indicate that the NVH size can be increased for fixed capsule radius while maintaining adequate drive to achieve ignition velocities. Increasing the case to capsule ratio in this way creates more room for the inner beams to propagate. Similarly using different shape hohlraums can reduce hohlraum wall plasma blow off in the path of the inner beams, improving the drive to the capsule equator. Finally, choosing an intermediate hohlraum gas density should also reduce hohlraum wall plasma filling, further improving inner beam propagation while keeping below thresholds for laser plasma instabilities. A series of 2D simulations indicate that by using all three of these tools, time dependent symmetry should be improved for pulses as long as 9ns. If this can be realized, it opens up the possibility of extending the promising NVH to 3-shock, lower adiabat (α ~ 2) HDC designs. A series of experiments are planned in 2014 to examine this parameter space.

5. Conclusion.

Significant progress in ICF implosion performance on NIF was seen in 2013 (see Fig. 10). Options to increase v_{imp} and hence the yield for the high foot target include increasing laser energy and power, using thinner ablators as well as DU hohlraums, and further fine tuning the CBET. We will also investigate CH high foot capsules in rugby hohlraums.

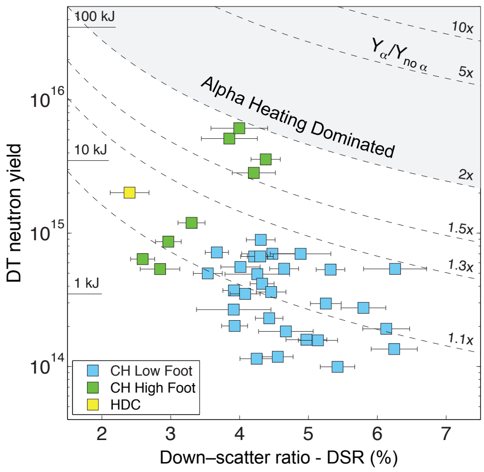

Fig. 10. Total neutron yield (13-15 MeV) plotted against DSR, the ratio of downscattered to unscattered neutrons. DSR is approximately proportional to the DT fuel ρr [21]. High foot, high adiabat (α~2.5) CH targets using a 3-shock design, (green squares) have demonstrated a total neutron yield of 6.3 x10^{15} (a fusion yield of ~ 17 kJ) with DT layered targets. This represents a near 10-fold increase over the low-foot CH design (blue squares). At a yield of 17 kJ, the yield from alpha self-heating for the high-foot design is ~ equal to the compression yield (the threshold for alpha self-heating). A DT-layered HDC target with a 7 ns, 2-shock (α~3.5) pulse in a near vacuum hohlraum achieved a yield of 1.8 x10^{15} (yellow square).

HDC ablators have been shown to perform well using both gas filled and NVH. Four-shock low adiabat (α~1.5) HDC capsules were imploded in conventional gas-filled hohlraums and produced higher quality implosions than equivalent CH designs. Both the 4- and 2-shock HDC capsules had very low mix and high YoC performance. The Near Vacuum Hohlraums provide an alternate path for higher adiabat implosions with very high velocities and little or no hotspot mix.

Rugby holraums have demonstrated uniform x-ray drive with minimal CBET and will be used with high foot CH designs.

We have made good progress in measuring and modeling growth of ablation front hydro instabilities.

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