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Results from neutron imaging of ICF experiments at NIF

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Results from neutron imaging of ICF experiments at NIF

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Abstract. In 2011 a neutron imaging diagnostic was commissioned at the National Ignition Facility (NIF). This new system has been used to collect neutron images to measure the size and shape of the burning DT plasma and the surrounding fuel assembly. The imaging technique uses a pinhole neutron aperture placed between the neutron source and a neutron detector. The detection system measures the two-dimensional distribution of neutrons passing through the pinhole. This diagnostic collects two images at two times. The long flight path for this diagnostic, 28 m, results in a chromatic separation of the neutrons, allowing the independently timed images to measure the source distribution for two neutron energies. Typically one image measures the distribution of the 14 MeV neutrons, and the other image measures the distribution of the 6-12 MeV neutrons. The combination of these two images has provided data on the size and shape of the burning plasma within the compressed capsule, as well as a measure of the quantity and spatial distribution of the cold fuel surrounding this core. Images have been collected for the majority of the experiments performed as part of the ignition campaign. Results from this data have been used to estimate a burn-averaged fuel assembly as well as providing performance metrics to gauge progress towards ignition. This data set and our interpretation are presented.

1. Introduction

The National Ignition Facility (NIF) is currently investigating the possibility of achieving thermonuclear ignition of a deuterium-tritium (DT) plasma [1]. The present strategy is to generate the required densities and pressures through indirect ablative compression of plastic (CH) capsules containing DT ice layers, which surround DT gas. In this design, the DT ice compresses a pocket of DT gas to temperatures of ~10 keV with total fuel densities, ρR, of greater than ~1 g/cm^2. With the appropriate fuel assembly conditions, this system is predicted to result in fusion processes starting in the compressed DT gas, generating a hotspot, which then initiates the propagation of an ignition front traveling through the surrounding “cold” high density DT fuel. This reaction would release over a megajoule of fusion energy and more than 10^{17} neutrons.

Tuning the implosion to achieve ignition requires the measurement of plasma conditions at very small length and time scales. The hot spot is predicted to have a 40-50 µm diameter and to maintain fusion conditions for ~100 ps, while the surrounding cold fuel is expected to be ~100 µm in diameter. Establishing the appropriate conditions for ignition, such as symmetry, hot spot and cold fuel volume,

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has required an iterative tuning campaign. These measurements must be made at non-ignition conditions, allowing the tuning effort to move from initial non-igniting implosions towards conditions required to achieve ignition.

The neutron imaging system is composed of an aperture array, used to form the neutron images, and a detector system that is used to measure the neutron flux passing through the pinhole array. The detector system [2,3] is capable of collecting two images, which are independently timed. With the detector positioned 28 m from the neutron source, the neutron arrival time is correlated to the neutron energies, allowing measurement of the neutron source distributions from two energy ranges by gating the detectors. Typically, one detector is gated to view the 14-MeV neutrons (13-17 MeV), which are generated from DT fusion processes, while the second detector is gated to measure the source distribution of lower energy neutrons typically in the range from 6-12 MeV. The ratio of the lower energy neutrons to 14 MeV neutrons is referred to as the down scatter ratio. These lower energy neutrons are predominantly DT fusion neutrons that have scattered in the surrounding cold fuel and, therefore, provide information on the distribution of cold fuel surrounding the hotspot. These two measurements provide the size and shape of the hotspot source as well as the surrounding cold fuel.

The scattering of 14 MeV neutrons, which have been generated by fusion reactions in the hot spot, within the surrounding cold DT fuel, results in a correlation between scattering angle and neutron energy. The kinematics of these scattering processes results in the detection of neutrons that have scattered in the cold fuel located on the same side of the fuel assembly as the neutron imaging line of site. Therefore, neutron images collected from scattered neutrons at lower energies provide a measure of the cold fuel distribution on the imaging side of the fuel assembly.

2. Results of Point Design Tuning Campaign

At NIF, dozens of experiments have been performed to tune the point design capsule performance toward thermo-nuclear ignition [4,5]. Neutron images were collected from each cryogenically layered implosion experiment. The neutron source distribution was calculated from each 14-MeV and 6-12 MeV neutron image, providing size and shape information of the hot-spot and cold fuel assemblies, respectively. Contours at 17% of the peak intensity were fit with Legendre polynomials to characterize the size and shape of each neutron source distribution [2,3]. The results of this fit provides a measure of the lowest mode of hot-spot asymmetry, P2/P0, which is the ratio of the second-order to the zeroth-order Legendre polynomials that are required to fit the 17% contour. Several experiments were performed to reduce this asymmetry [6], as implosion symmetry is believed to be one of the important parameters in achieving ignition. Figure 1 shows a plot of neutron yield as a function of hot-spot source asymmetry P2/P0 for NIF point design experiments. There is no clear correlation observed between the neutron yield and the hot-spot asymmetry, in disagreement with previous experiments and code predictions for capsule performance [4]. It is important to note, however, that implosion symmetry is not the only change in each of these experiments and other performance characteristics could be dominating performance, which would hide the underlying correlation between shape and performance.

It is instructive to look at the fuel assembly for a subset of the experiments that have been summarized in Figure 1. The images that have been chosen here are of one of the most symmetric fuel assemblies (NIF shot number N120321) and one of the most oblate fuel assemblies (NIF shot number N130331). The symmetric shot resulted in a neutron yield of $4.2\text{x}10^{14}$ neutrons, an ion temperature of 3 keV and a down scatter ratio of 6%, while the oblate shot yielded $3.0\text{x}10^{14}$ neutrons, an ion temperature of 3 keV and a down scatter ratio of 4%,. There are many variables beyond shape that can impact performance. One example is mix; where hydrodynamic instabilities move the CH capsule and dopant material into the hotspot and reduces the yield [7]. In the experiments shown in Figure 2, the inferred mix values [8] were 370±150 ng and 50±50 ng for the symmetric and asymmetric experiments, respectively. Although not directly observed, it is likely that processes such as mix of the ablator material into the hotspot has led to a larger impact on performance than the shape of the hotspot, explaining the lack of correlation between hotspot symmetry and the resulting yield.

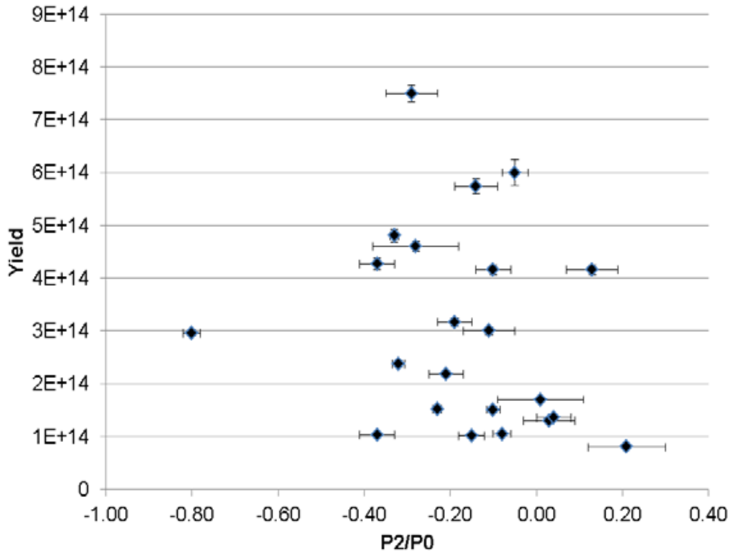

Figure 1: Neutron yield versus asymmetry, P2/P0. There is no clear correlation between yield and symmetry in disagreement with previous experimental results and simulation predictions. This lack of correlation may be explained by other performance parameters dominating the yield performance of the ignition point design.

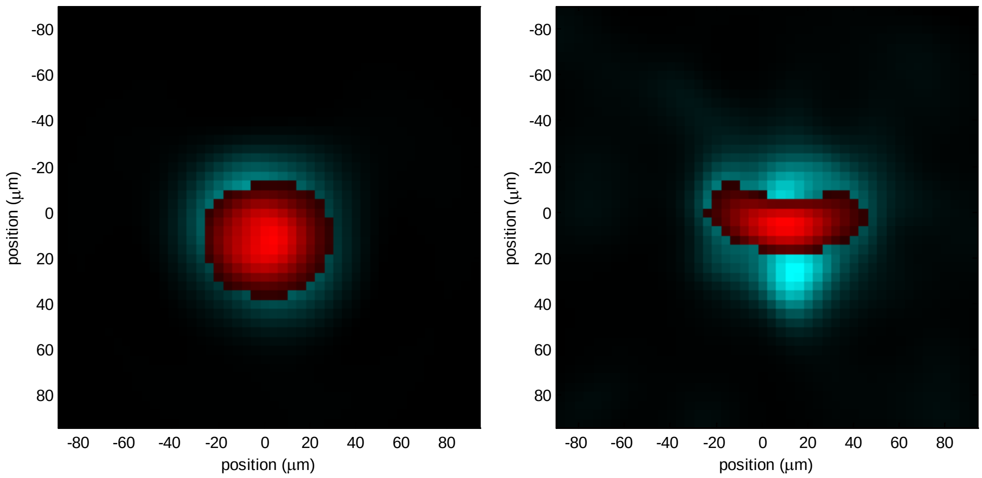

Figure 2: Left: fuel assembly measured from N120321 with a P2/P0=-0.10 and Right: fuel assembly from N130331 with P2/P0=-0.80. In these images the hotspot sources are shown in the red channel and are overlaid with an image of the cold fuel, which is displayed in the cyan channel. The shot on the left resulted in a yield of 4.2×10^{14} neutrons, an ion temperature of 3 keV and a down scatter ratio of 6%, while the shot on the right resulted in 3.0×10^{14} neutrons, an ion temperature of 3 keV and a down scatter ratio of 4%. Red intensity is proportion to yield while cyan intensity is proportion to the product of yield and down scatter ratio.

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3. Results of High-Foot Tuning Experiments

More recently a series of “high foot” experiments has been executed at NIF to study the performance of implosions that intentionally drive the fuel along a higher adiabat than the point design. It has been predicted that these experiments should result in reduced mix of the ablator into the hot spot. Three images from the initial tuning experiments in this series (N130802, N130710 and N130812) are shown in Figure 3. The yields from these experiments were 4.8×10^{14}, 1.0×10^{15} and 2×10^{15} neutrons, respectively, while the inferred mix levels were 0±150 ng, 0±150 ng and 84±35 ng respectively. Ion temperature and down scatter ratio are reported in the figure caption below. In these experiments there is a clear correlation between the symmetry of the fuel assembly and performance as well as an observation of reduced ablator mix. The emergence of this correlation is consistent with mix, rather than the shape of the fuel assembly, dominating the performance of the point design.

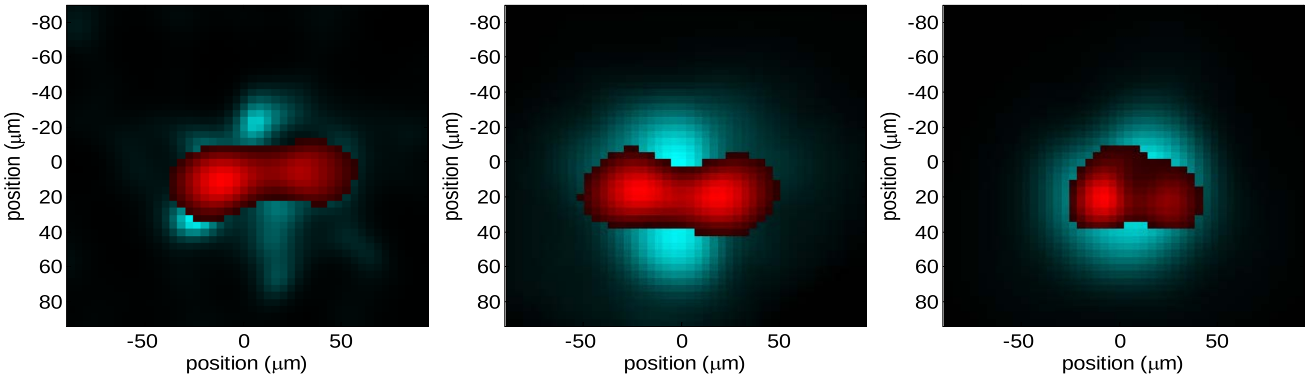

Figure 3: Hotspot sources are shown in the red overlaid on images of the cold fuel shown in cyan. Left (N130802) resulted in a P2/P0=-0.67, 4.8×10^{14} neutrons, ion temperature of 3 keV and down scatter ratio of 3%, middle (N130710): a P2/P0=-0.25, 1×10^{15} neutrons, ion temperature of 3.5 keV and down scatter ratio of 3% and on the right (N130812): P2/P0=-0.25, 2.4×10^{15} neutrons, ion temperature of 4 keV and down scatter ratio of 4%. Red intensity is proportion to yield while cyan intensity is proportion to the product of yield and down scatter ratio.

4. Conclusions

Throughout the tuning efforts at NIF, the fuel assembly has been measured through the collection of neutron images for a large number of experiments. For the point design experiments, there is no observed correlation between performance, as measured by yield, and the shape of the hot spot. This lack of a correlation suggests that other processes are dominating the performance. Although not observable through neutron images, one possible process is mixing of the ablator material into the hot spot. This hypothesis is strengthened through the recent measurements of the high-foot series of experiments, where less mix has been observed along with an emerging correlation between symmetry of the fuel assembly and performance as measured by yield.

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