

First downscattered neutron images from Inertial Confinement Fusion experiments at the National Ignition Facility

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Abstract. Inertial Confinement Fusion experiments at the National Ignition Facility (NIF) are designed to understand and test the basic principles of self-sustaining fusion reactions by laser driven compression of deuterium-tritium (DT) filled cryogenic plastic (CH) capsules. The experimental campaign is ongoing to tune the implosions and characterize the burning plasma conditions. Nuclear diagnostics play an important role in measuring the characteristics of these burning plasmas, providing feedback to improve the implosion dynamics. The Neutron Imaging (NI) diagnostic provides information on the distribution of the central fusion reaction region and the surrounding DT fuel by collecting images at two different energy bands for primary (13–15 MeV) and downscattered (10–12 MeV) neutrons. From these distributions, the final shape and size of the compressed capsule can be estimated and the symmetry of the compression can be inferred. The first downscattered neutron images from imploding ICF capsules are shown in this paper.

1. INTRODUCTION

A neutron imaging system [1, 2], together with several other diagnostics [3], was developed for the ICF experiments at the National Ignition Facility. The system recently started to provide data from the experiments by imaging the primary and downscattered neutrons from the implosions. The neutrons generated during the fusion reactions are transported through an array of 23 pinhole and mini-penumbral

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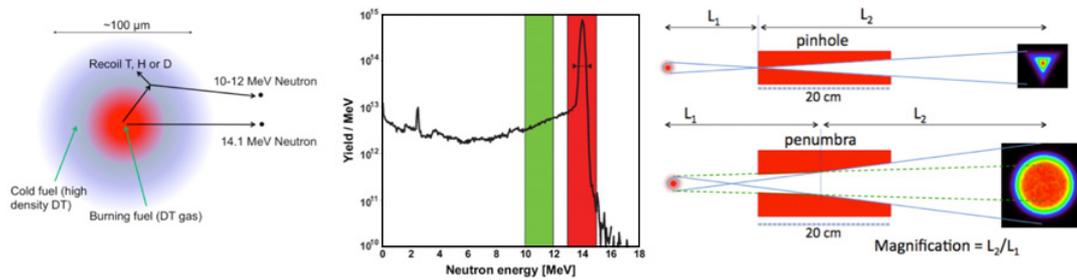


Figure 1. A cartoon of an imploding DT capsule is shown (left) together with the expected neutron energy spectrum from the burning capsule (middle). Neutrons are emitted from DT fusion reactions in the burning region (central part) and some of them are scattered in the cold fuel region, sampling the cold fuel distribution. Temporal separation of neutrons after 28 m drift results in ability to collect two neutron images, primary (13–15 MeV) and downscattered (10–12 MeV), by using pinhole and penumbral apertures (right) with a gated imager system.

apertures embedded into a 20 cm thick gold attenuator. The apertures are tapered through the attenuator and their fields of view intersect 26.5 cm in front of the aperture body. In the current configuration, the aperture body is positioned with its front surface at 32.5 cm from the source. As a result, each pinhole points to a slightly different location at the source plane [1]. The neutron signal is converted into light by a bundled array of scintillating fibers positioned at 2802.5 cm from the source. This configuration provides a magnification factor of ~ 85 for the pinholes and ~ 66 for the penumbral apertures because of their internal structure within the attenuator (see Fig. 1). These imaging techniques have been studied and explained in various publications [4–8]. The light from the fibers is collected by two fast gated camera systems [1]. As shown in Fig. 1, the primary neutrons are emitted from DT fusion reactions with 14.1 MeV and their energy spectrum is broadened by the thermal motion of the parent nuclei. The primary neutron camera is gated to collect signals from 13–15 MeV neutrons. As primary neutrons pass through the high density cold fuel region, they lose energy by scattering. Their distribution provides information about the cold fuel [9]. The second camera is gated to collect signals from these downscattered neutrons in 10–12 MeV range. This range was chosen to minimize the background from interactions other than scattering and to maintain statistics [9]. The 28 m distance between the source and the detector provides 43 ns difference between the arrivals of the 14 MeV and the 12 MeV neutrons, making it possible to image the neutron distributions from two different energy bands. Simultaneous collection of the primary and downscattered images from imploding ICF capsules was performed for the first time at the NIF and the results are shown in this paper.

2. IMAGE ANALYSIS

The main objective is to analyze the collected images to reconstruct the source distribution and extract the shape and size of the imploding capsule. The main focus of this paper is the cold fuel distribution. Figure 2 shows the two images collected with the aperture array. Before the source reconstructions, background corrections and normalizations were applied to the images. For this reason, series of dark field images were collected before and after each shot, with the same camera settings, to measure the baseline levels in the CCD cameras. They were averaged and subtracted from the images. Occasionally, direct nuclear interactions with some pixels in the CCD show themselves as saturated signals. Those pixels were corrected by taking the average of the neighboring pixels. Less than 0.1% of the pixels were affected from this procedure. In addition, flat field images were collected in calibration shots for both cameras [1] to measure the signal from a uniform distribution of neutrons. The images were divided by the flat field images to correct for varying response of the detector elements across the fiber array. After alignment of the downscattered image to the primary image, the intensities for each pixel were corrected

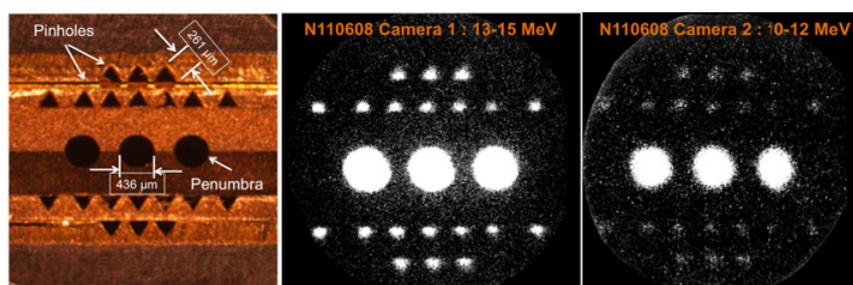


Figure 2. The aperture array (left) and the raw images collected on shot N110608, showing 20 pinholes and 3 penumbral images for the two cameras gated on 13–15 MeV primary neutrons (middle) and 10–12 MeV down-scattered neutrons (right).

for the residual light present in the plastic scintillator from the decay of the primary neutron signal. Direct drive exploding pusher implosions with small areal density ($\sim 10 \text{ mg/cm}^2$) produce negligible amount of downscattered neutrons. They provide the data for measuring the residual tail of the primary neutron signal in the scintillator at the arrival time of the downscattered neutrons. By using the signal from the penumbral apertures, the residual light background was measured to be $0.65 \pm 0.20\%$ in the 10–12 MeV range.

The current yields from layered cryogenic DT implosions is generally on the order of few 10^{14} neutrons. The ratio of 10–12 MeV neutrons to the primary neutrons, referred as the down-scattered ratio (DSR), is mostly around 5% for these shots. The measurement of this ratio from the penumbral images is consistent with independent measurements made by the neutron time-of-flight (TOF) detectors to within 10%. The current signal levels required the use of the penumbral apertures to observe the distribution of the downscattered neutrons. The first step in the reconstruction is to determine the alignment of the selected aperture with respect to the source and produce the appropriate point spread function (PSF). The pointing information was obtained using several different techniques. The first one uses the fact that the pinholes point to different locations at the source plane, resulting in varying transmission through each pinhole for a given source location. MCNP [10] calculations for the expected transmission from various source location are compared to the data to extract pointing. The second technique uses the change of the shape of the penumbral images due to the source location. In addition, using the magnification difference between the pinhole and penumbral apertures also provides an estimate of the source location. The PSF was obtained by calculation of neutron transmission through the aperture using MCNP simulations. Then the image was inverted with an iterative "Expectation Maximization Maximum Likelihood" (EMML) [11] technique to obtain the intensity profiles of the burn region and the surrounding high density fuel. The estimated distributions were fitted to Legendre modes at the 17% contour to calculate the size and shape of the hot spot from the primary image and that of the cold fuel from the downscattered image.

Figure 2 shows the data taken on the shot N110608 for both cameras. The middle penumbral images were reconstructed. The results are shown in Fig. 3. The first Legendre fit coefficient, P_0 , at the 17% contour provides the average radius of the source distribution. The reconstructions show that this particular implosion generated a hot spot with average radius of $34 \pm 1 \pm 4 \mu\text{m}$ and a cold fuel with radius of $49 \pm 8 \pm 4 \mu\text{m}$. The $4 \mu\text{m}$ systematic error on these reconstructions comes from the PSF used for the reconstruction and includes possible uncertainties in the alignment and aperture shape. Knowing the initial size and mass of each layer of this capsule and assuming mass was conserved during the compression, the spatially averaged cold fuel density can be calculated from the sizes measured by the neutron images. For this implosion, the cold fuel density was $\sim 513 \text{ g/cm}^3$. From the observed shell thickness, the areal density ρR was calculated and compared with officially inferred values from TOF

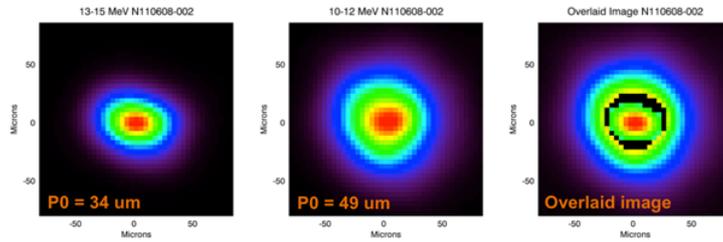


Figure 3. The reconstruction results from the middle penumbral images of N110608 shot data, shown in Fig. 2. The reconstructed hot spot (left) and cold fuel (middle) distributions as well as their overlay (right) provide information about the compression symmetry. The rightmost figure represents the 2D projection of the imploding ICF capsule at the stagnation point. The average radius is obtained by fitting these images at the 17% contour and extracting the first Legendre coefficients. The overlaid picture is a direct overlap of the two images after some manipulation of the colors in the hot spot image, in order to make both images equally visible.

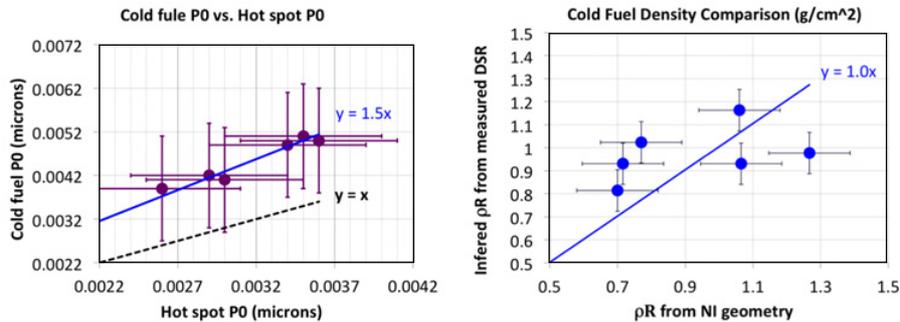


Figure 4. The cold fuel radius vs. hot spot radius are shown for various shots (N110603, N110608, N110615, N110620, N110826 and N110914). The linear fit with a slope of 1.5 suggests that the cold fuel shell thickness after the compression is half the size of the hot spot radius for most shots. Changing the drive conditions does not seem to affect the overall compression ratio significantly. Since we know the initial capsule size and mass in each layer, we can calculate the final average cold fuel areal density, ρR , by using the NI results. These calculations are compared to the values inferred from the measured DSR by the neutron TOF detectors.

detectors. Those results are shown in Fig. 4. The same calculation for the shot N110620 gives 975 g/cm^3 average cold fuel density. This value is close to the ignition conditions provided by hydra simulations [12].

3. CONCLUSIONS

High density cold fuel distributions of imploding ICF capsules were reconstructed from downscattered neutron images for the first time. The results have reasonable agreement with the inferred values from the neutron TOF detectors. These inferred values, however, are for spatially averaged areal densities. This will not account for a possible non-uniform distribution of the cold fuel around the hot spot, which can result in a non-uniform energy deposition from α particles, causing a heat loss and preventing ignition. Neutron imaging results can provide the information about density distribution around the hot spot as well as the relative location of the hot spot inside the cold fuel.

The current yields are usually not high enough to reconstruct the down-scattered neutron intensity profiles using the pinhole apertures. The results shown here are from penumbral apertures, which have three times more signal than the pinholes on average. We are working on combining pinhole signals to

increase the image strength to reconstruct the cold fuel distribution from the pinhole images. This will increase our confidence on the reconstruction results and hopefully reduce the error bars.

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