Neutron Imaging Development for MegaJoule Scale Inertial Confinement Fusion Experiments

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Abstract. Neutron imaging of Inertial Confinement Fusion (ICF) targets is useful for understanding the implosion conditions of deuterium and tritium filled targets at Mega-Joule/Tera-Watt scale laser facilities. The primary task for imaging ICF targets at the National Ignition Facility, Lawrence Livermore National Laboratory, Livermore CA, is to determine the asymmetry of the imploded target. The image data, along with other nuclear information, are to be used to provide insight into target drive conditions. The diagnostic goal at the National Ignition Facility is to provide neutron images with 10 $\mu$m resolution and peak signal-to-background values greater than 20 for neutron yields of $\sim 10^{15}$. To achieve this requires signal multiplexing apertures with good resolution. In this paper we present results from imaging system development efforts aimed at achieving these requirements using neutron pinholes. The data were collected using directly driven ICF targets at the Omega Laser, University of Rochester, Rochester, NY., and include images collected from a $3 \times 3$ array of 15.5 $\mu$m pinholes. Combined images have peak signal-to-background values greater than 30 at neutron yields of $\sim 10^{13}$.

1. Introduction
To obtain ignition at Inertial Confinement Fusion laser facilities requires an energetically efficient compression of deuterium and tritium fuel. Ideally this compression would be spherical. However, the cylindrical hohlraum and temporal profiles of the required laser shocks, due to thermodynamic and hydrodynamic constraints[1], cause the fuel configuration at peak compression to vary. Studies have shown this variation can depend on laser drive conditions and deviate significantly from a sphere[2, 3, 4, 5]. Neutron imaging can be a useful diagnostic for determining the nature of the drive conditions. For the National Ignition Facility at Lawrence Livermore National Laboratory, two complementary imaging systems are being designed. These are referred to in this text as the “hot” and “cold” fuel imaging systems respectively. Fuel actively undergoing $t(d, n)\alpha$ reactions is referred to as “hot-fuel,” while the fuel not producing neutrons, but acting as a scattering source is referred to as “cold-fuel.”

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| Energy Gates          | Hot Fuel (0 − 14.5 MeV) | Cold Fuel (6 − 10 MeV) |
|----------------------|-------------------------|------------------------|
| Spatial Resolution   | 10 µm                   | 10 µm                  |
| Peak Signal-to-Background | 22                     | 22                    |
| 15% Contour Signal-to-Background | 10                     | 10                    |
| Energy Resolution    | 0.3 MeV @ 10 MeV        | 0.3 MeV @ 10 MeV      |
| Yield within Energy Band | 5E + 15 − 1E + 19       | 5E + 14 − 1E + 18     |
| Minimum Field-of-View| 100 µm                  | 150 µm                |
| Dynamic Range        | 100:1                   | 100:1                 |
| Sensitivity          | 20%                     | 20%                   |

Table 1. The neutron imaging system performance requirements for the National Ignition Facility.

2. Neutron Imaging at the National Ignition Facility

Requirements for the National Ignition Facility (NIF) neutron imaging system are outlined in Table 1. These requirements were determined by analyzing simulated source images. The resolution and signal-to-background estimates were arrived at by distorting the images until important structural elements were no longer discernible by eye. The distortions included smearing the image with gaussian filters of varying full-width-half-maximum and changing the signal-to-background level of contours of constant intensity. Recently fielded neutron imaging systems have calculated resolutions of ∼ 20 µm with a peak signal-to-background of ∼ 40[6] for annular and penumbral imaging and ∼ 25µm with a signal-to-background of ∼ 30 using pinhole imaging. Further development is needed to fully meet the requirements of the NIF.

3. Neutron Imaging Progress at Los Alamos National Laboratory

Efforts at Los Alamos National Laboratories have focused on constructing arrays of pinholes. Pinholes provide a direct measurement of the source, and it is relatively straightforward to add multiple images together to achieve gains in signal-to-background performance. As a result, arrays of pinholes are many times more efficient than other apertures at discrimination tasks[7].

It is anticipated that as many as 50 pinholes may be required to image the hot and cold fuel respectively. Previous efforts at Los Alamos have produced a 1−dimensional array of two pinholes[8]. These apertures were made by precision machining grooves into faced Au layers that had been electroplated onto matched W plates. The apertures were formed by aligning the opposing grooves and pinning the assembly together like a ”sandwich.” Since the effective aperture diameter must be close to the resolution requirements of the imaging system, assembly tolerances of a few microns in this sandwich process introduce a significant uncertainty in the point-spread-function of the aperture. Once assembled, it is difficult to metrologize the ”as-built” aperture to correctly determine the new aperture shape for image analysis. Further, extending this process to a second dimension to produce a compact array of apertures was deemed impractical.

To address these concerns a simpler process was developed. Grooves are precision machined with a 60° diamond tool having a 5 µm radius into wedge shaped layers of Au which are then assembled in a “layer-cake” like process. The aperture shape is defined by the triangular-cross-sectioned-grove and the flat surface of the layer above. Prior to assembly, the grooves may be metrologized, and to first approximation, the assembly process allows for an accurate description of the aperture point-spread function. This process is described in more detail in reference[9] and is illustrated in Fig. 1(a). Fig. 1(b) shows the three grooved Au components.

The axis of each aperture was designed to focus on the target at a distance of 21cm from the front of the assembly and diverge from this point with a 1 mrad angular spacing on a square grid. At the Omega Laser facility, this places images 1.3 cm apart in the imaging plane. The cross section of an aperture at each position along its axis forms an equilateral triangle, that when projected into the object plane, has sides 205 µm in length. A circle inscribed about the
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(a) Isometric view of the array components.  (b) Machined components prior to assembly.

**Figure 1.** Components of a 3 × 3 array of pinholes of 15.5 µm triangular cross-section pinholes. The array of aperture centroids intersect at a point 21 cm in front of the assembly and diverge to the recording station at an angle of 1 mrad.

(a) Raw neutron image from 3 × 3 array of pinholes.  (b) Sum of three bottom images without filtering.  (c) Sum of three bottom images with filtering at -3dB.

**Figure 2.** A minimally processed neutron image using a 3 × 3 array of pinholes on shot 46827 at the Omega Laser. The image is of an imploded spherical, CH shell with an initial outside diameter of 865 µm and a wall thickness of 16 µm, filled with an 82.6% − 17.4% deuterium-tritium mix at 5atm. The total laser energy of 23.3 kJ was delivered in a 1 ns square pulse. The shot yield was $2.5E+13$ neutrons.

centroid has a diameter, at the object plane, of $\sim 118$ µm. The effective diameter of an aperture was calculated to be 15.5 µm.

The first neutron image of an inertial confinement fusion target using a 2−D array of pinholes is shown in Fig. 2(a). The image was taken using the aperture described above. It has been minimally processed by removing stars, subtracting both electronic pedestal and backgrounds, correcting for response nonuniformity, normalizing for yield, and low-pass filtering (-3dB) to reduce fixed-pattern noise in the recording system. Shot specifics are given in the figure caption. The orientation of the images is similar to that shown in Fig1(b) above. The horizontal rows of images are taken from pinholes within each of the three layers made during assembly. The top row of images were collected by the layer of inverted apertures. Within each row, the mean column-to-column spacing between centroids of the images was measured to be 1.31 cm which was expected given the tolerances of the manufacturing technique. The mean row-to-row spacing varied significantly from the design tolerances due to unforeseen difficulties with thermal expansion in the Cu plates during electro-plating and machining. This very slightly warped the resulting grooved Au foil (middle row of images) and more substantially warped the spacer foil between the middle and top row of images. The mean distance measured between centroids of the bottom and middle row of images was 1.27 cm, while a mean distance of 1.05 cm was measured between the middle and top row of images. The FWHM in the source plane of the
brightest image in the array was 47 $\mu$m. The recording system used to capture the image has a resolution measured to be 19 $\mu$m in the source plane, which gives an estimated image resolution of $\sim 25$ $\mu$m based on a pinhole diameter of 15.5 $\mu$m.

From left to right in the bottom row of the array image, the number of detected neutrons in the peak resolution element was $390 \pm 20.6$, $449 \pm 22.1$, and $410 \pm 21.1$ neutrons respectively, giving peak signal-to-background numbers of 18.9, 20.3, and 19.4. The mean number of detected neutrons in the bottom row was 417 with a standard deviation of 31. The discrepancy between the variation of the mean signal when compared to the statistical uncertainty of individual apertures is attributed to small manufacturing difference between apertures within a layer, resulting in slightly more material between the target and aperture. This discrepancy is equivalent to $\sim 150$ $\mu$m variation of Au, which was observed during manufacturing. Fig. 2(b) shows the results of adding the three bottom images prior to the -3dB filtering step. A suitable region around each aperture image was defined, and the three images were then registered to each other using the positions of the calculated centroids and known separations. The image in Fig. 2(c) is the resulting sum, after low-pass filtering. The resulting image has a peak signal-to-background of 34.0.

4. Conclusions
Images from the first $2-D$ array of neutron pinholes for Inertial Confinement Fusion experiments have been obtained. The array used was contained a $3 \times 3$ distribution of 15.5 $\mu$m diameter pinholes, yielding individual images with signal-to-backgrounds of $\sim 21$. Three images were combined to yield an image with a signal-to-background of 34. To fully exploit the capability of these 15.5 $\mu$m apertures, the recording system resolution must be improved above it’s current 19 $\mu$m resolution in the object plane. This may be readily accomplished by reducing the scintillating fiber diameter of the radiation-to-light converter, which will improve the imaging system resolution in the source plane to $\sim 13$ $\mu$m. A corresponding imaging system fielded at the NIF would theoretically be capable of achieving raw images with a resolution of 16.1 $\mu$m while exceeding the signal-to-background requirements. With appropriate reconstruction techniques, the resolution may be improved to close to the 10 $\mu$m requirement.

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