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Aperture design for the third neutron and first gamma-ray imaging systems for the National Ignition Facility[a)]

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The current construction of a new nuclear-imaging view at the National Ignition Facility will provide a third line-of-sight for hotspot and cold fuel imaging and the first dedicated line-of-sight for 4.4-MeV γ-ray imaging of the remaining carbon ablator. To minimize the effort required to hold and align apertures inside the vacuum chamber, the apertures for the two lines of sight will be contained in the same array. In this work, we discuss the system requirements for neutron and γ-ray imaging and resulting aperture array design.

I. INTRODUCTION

The shapes of the 14.1-MeV neutron emission and the 4.4-MeV γ-ray emission created in DT fusion experiments at the National Ignition Facility (NIF)[1] are key measurements for understanding the performance of the implosions. At present there are Neutron Imaging Systems on the equator (NIS)[2] and on the north pole (NIS-NP)[3] of the chamber. They are aperture imagers similar to optical pinhole cameras but with thick apertures and thick detectors suitable to particles with high penetration. Energy resolution is obtained via time of flight and gated detectors. The two views provided by these imagers have provided limited understanding of the nature of the implosions, but a third view approximately perpendicular to the existing lines of sight is needed to provide three-dimensional data. This new system, known as NIS3, is currently under construction and will be the third generation of neutron imaging systems at the NIF.

Information about the remaining ablator can also be obtained by imaging 4.4-MeV γ-rays produced by scattering of the fusion neutrons from carbon in the remaining ablator. This γ-ray imaging has been demonstrated in tests with NIS by gating the detectors for the photon arrival time. Thus, NIS3 will include a line of sight for γ-ray imaging as well as the line of sight for the neutrons.

NIS3 will be the first of these systems specifically designed to capture γ-ray, x-ray and three types of neutron images simultaneously. These five types of images require specific apertures, optimized for the specific characteristics of the particle that is being imaged. Therefore, the aperture array design is dictated by a wide range of requirements. The following sections will walk through these requirements and the solution to the design. The requirements for the NIS3 pinhole array (PHA) are similar to requirements from the NIS and NIS-NP arrays[4,5], with some new requirements for the γ-ray images and some optimization based on lessons learned in the manufacture and deployment of the NIS-NP system. Comparisons of simulations and real data on the NIS-NP system gives us confidence that the simulations accurately predict the result of changes to the PHA design. Therefore, through extensive simulation and modeling of this design, we have optimized the layout and features of the PHA to best use the space available in the PHA and on the recording systems. In this work, we discuss the NIS3 requirements and how the design works to meet these requirements.

II. EXTERNAL REQUIREMENTS

The requirements for the external size and features of the pinhole array (PHA) are similar to previous versions in that the size and shape must be minimized to provide clearance to other instruments. The PHA must be able to be aligned to the source and detector planes in a structurally stable manner, in order to survive the blast loading during a high yield shots. In addition, the PHA, including the protective cover must provide sufficient clearance to target holder, shrouds and beams. At the 90-212.5 line of sight, these requirements combine to limit the location of the front of the PHA to 29cm from target chamber center (TCC). For comparison the offset distance for NIS-NP is 20cm and NIS is 32.5cm.

As discussed in Section III.C, the maximum-likelihood reconstruction of the images requires precise understanding of the pointing and shape of the apertures in the array. Due, however, to the high aspect ratio of the apertures, the field of view of an individual aperture is largely set by the projection of the aperture at the source, so multiple apertures are used to create a larger effective field of view. Even with a larger field of view, the alignment of the PHA is critical. While the NIS uses a telescope on the opposite port for alignment, NIS-NP uses a laser tracker system known as ATLAS to perform the alignment, and NIS3 will also use ATLAS.

The snout that holds the PHA in the chamber has enough movement in five degrees of freedom that we can use machined tolerances to mount the PHA to the snout. Features used to calculate the central axis and aim point of the PHA are required to be visible with an optical coordinate

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measuring machine. This makes it possible to mount the PHA to a snout and relate the axis and aim point to the ATLAS retro reflectors.

III. INTERNAL REQUIREMENTS

A. Recording media size and location

The NIS3 recording systems consists of a suite of detectors distributed along the length of the 26-m lines-of-sight. The γ-ray LOS differs from the neutron LOS by .5°, split on either side of the 212.5 central axis. Figure 1 shows the relative locations of the detectors. Each recording system is placed within 2mm of the designed location. The size of each detector defines the maximum projected size of the images through the apertures including a margin on the edges for alignment tolerance accommodation.

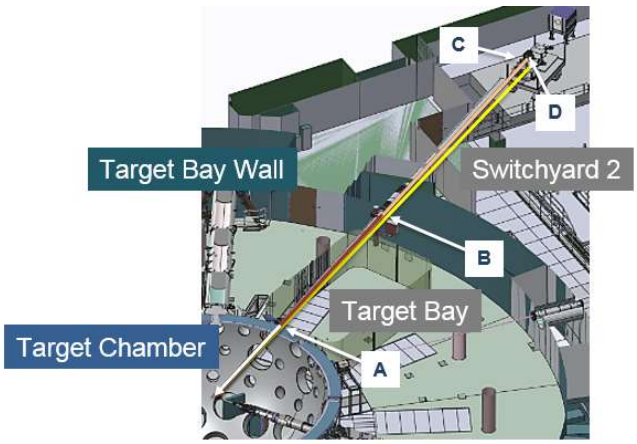

Figure 1: Locations of recording systems for NIS3: (A) X-ray and neutron image plate detector, (B) Neutron image plate detector, (C) Neutron scintillator detector, (D) γ-ray scintillator detector.

Location (A) is on the port cover of the chamber, the detector stack is located inside the vacuum 5.5m from TCC, and collects x-ray and time-integrated neutron images. The detector plates are 10cm square, and consist of layers of carbon, image plate (IP), 6 sets of polyethylene and IP, similar to what is used on CNXI [6,7]. Location (B) is on the inside of the target bay wall, ~15.5m from TCC. The detector stack collects time-integrated neutron images on a 25cm x 30cm polyethylene/IP stack.

Locations (C) and (D) are in NIF Switchyard 2, ~26m from TCC. These detector systems collect the γ-ray, primary neutron and down-scattered neutron images. These are active detector systems with scintillators that are lens coupled to one or more gated optical detectors consisting of MCP and CCD cameras. The two scintillators are aligned to either the neutron or γ-ray LOS, staggered slightly along the length of the line of sight. Each scintillator is 2cm thick, with material optimized for the expected signal. Specific material details are left to other [X] and upcoming publications. The signal from the neutron scintillator is collected from both the front and back sides, as the primary image is significantly brighter, requiring the two image types to be collected from the same scintillator and compared in order to analyze the down-scattered image. Both neutron and γ-ray scintillators are 20cm square. This location provides the needed magnification and propagation time delays between signal types, without leaving the confines of the NIF building.

B. Source type, size and resolution

Each image type has a resolution driving the design of the aperture. These are described in table 1.

TABLE I. Resolution requirement by type

Type	Source Dia. (μm)	Resolution (μm)
Primary Neutron (12-14 MeV)	60μm	10μm
Down-scattered Neutron (6-10 MeV)	150μm	15μm
γ-ray (4.4MeV)	300μm	15μm

C. Alignment & Analysis

To reconstruct the source image from the recorded images, the location of the source with respect to the PHA must be calculated. This is accomplished by comparing the locations of the multiple images produced by the array of apertures. The images shift in both location and spacing depending on the source location. Using apertures with different magnifications further refines the understanding of the source location, as the relative shifts of the images provide information about source location.

The extended length and high aspect ratio of the individual apertures makes the FOV of each aperture finite, unlike typical pinholes. In order to achieve the required resolution, the FOV needs to remain small. Due to variations of target location, and PHA alignment the combined FOV of the aperture array must be at least a 700μm diameter for commissioning activities, and a 500μm diameter while in operations status. The number and pointing of the apertures in the array accommodate an alignment tolerance of +/-100μm on the front and back, in X and Y, and +/- 250μm along the axis, Z. This is within the limits of the ATLAS. The snout that holds the PHA in the chamber has enough movement in five degrees of freedom that we can use machined tolerances to mount the PHA to the snout, and characterize it to the retro reflectors.

Due to the separate scintillators for the neutron and γ-ray images, each image type must have penumbra included in the aperture. The pinholes provide a higher resolution image than the penumbra, but also allow significantly less signal through, requiring summing of multiple images to improve signal to noise characteristics.

The shape of the aperture must be well understood to deconvolve the images. This is done via metrology of the individual apertures during fabrication, prior to assembly. The variations in the machining of the apertures causes perturbations in the data requiring manipulation prior to summing. In addition the small shift in pointing between each aperture causes the images to not be able to be directly summed. The 20-cm long length of the aperture means that the images are very sensitive to their location in the aperture opening (non-shift invariant). All the design, metrology and actual data must be collected into a 3D model of the system which is used to deconvolve the source images. In addition, the orientation of the data must be well understood.

Previous experience has mandated providing a permanent feature in the data to clarify image orientation. Each type of aperture therefore must have a significant asymmetry so the orientation of the data is never in question.

IV. DESIGN SOLUTION

The full aperture consists of 87 individual apertures, where 11 of the apertures are dual use. There are 12 gamma penumbra, 3 neutron penumbra, 72 neutron pinholes and 11 x-ray pinholes. Descriptions of each type will be described in the following sections separated by type for clarity. A summary of the key parameters is provided following this section in table 3. The PHA is manufactured like previous apertures, with the apertures cut lengthwise in long, gold foils, with multiple apertures per layer. This aperture consists of 14 gold foil layers sandwiched between two structural tungsten layers. The layer thicknesses are summarized in table 2. Figure 2 shows the aft end view of the PHA, looking toward TCC. The features are the largest and easiest to see on this end. The layers are shown vertical, as this is the orientation when in use. Tables 3 and 4 provide a summary of all the aperture characteristics.

TABLE II. Layer thickness

Layer identifier	Front Thickness (µm)	Back Thickness (µm)
Layers 1, 14	500	500
Layers 2, 3, 4	454	709
Layer 5	921	1,746
Layers 6, 8, 11, 13	200	200
Layers 7, 12	221	503
Layers 9, 10	362	677

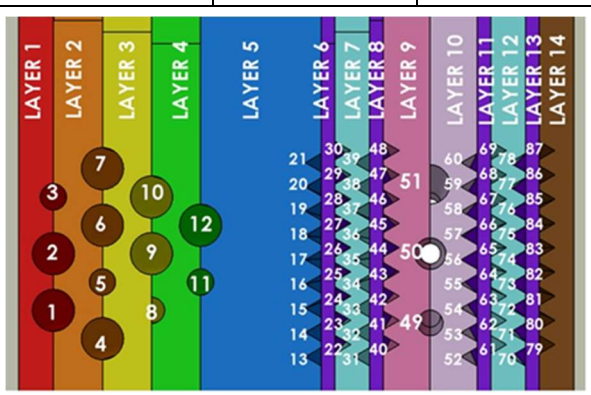

Figure 2: Model view of the back of the PHA, each aperture is identified with a unique number, as labeled. Colors to clarify layer boundary, all colored layers are made from gold. Shown without x-ray foils, with layers identified.

A. Neutron Apertures

The neutron apertures include all the apertures #13 thru #87, and can be divided into two sub-types: triangular pinholes and circular or semi-circular penumbral apertures. Note that while the arrangement of pinhole apertures is symmetric, the arrangement of penumbral openings provides a significant asymmetry, which will always accompany pinhole images.

1. Neutron Pinholes

The 72 pinholes consist of a triangular groove, with an initial depth of 15µm, tapering to a depth of 230µm (visible in figure 2). These dimensions correlate to an individual field of view of 200µm in the source plane. All the neutron pinholes have the same magnification, based on the front position of the PHA 29cm from TCC. Table 4 provides a summary of all the apertures size, magnification and FOV. There are eight columns of pinholes, each containing 9 pinholes. Each column of pinholes is oriented in the opposite direction, which helps correct the triangular distortion when the images are analyzed.

The long aspect ratio of the pinhole apertures means each pinhole has a specific aim point in the source plane. The pinholes are pointed to a staggered 25µm x 15µm grid, centered on the TCC, which provides a combined field of view of 500µm, as shown in figure 4. In addition, due to the penetrating nature of the neutrons, the coverage really extends to 700µm, although the fidelity of the images on the far extents may be degraded. This extended field of view is large enough to accommodate any errors made during commissioning and alignment. The long aspect ratio also means that the images will be projected to a specific place in the recording planes. Figure 3 shows the layout of the aperture FOV projections, at the target bay wall location. Note that the actual images do not fill the projected FOV area, so will not overlap when collected.

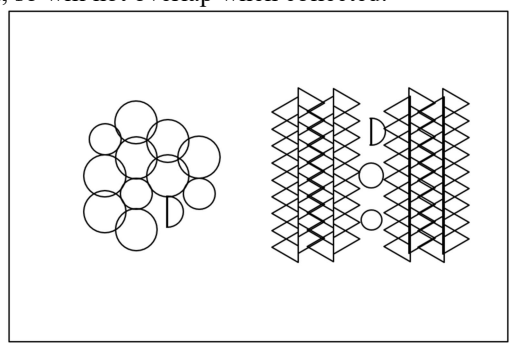

Figure 3: Projection of aperture FOVs on the image plate at the target bay wall (B) location.

2. Neutron Penumbral Apertures

The three neutron penumbral apertures each have a field of view of 300µm, with aim points vertically spaced by 120µm. The central penumbra is a defining feature of the PHA, as it is the primary feature used to align the array of apertures. Again, because of the penetrating nature of the neutrons, the overall field of view meets the 500-700µm requirement. These apertures start with a 300um diameter straight opening which continues until the waist of the aperture, after which the groove is conical, correlating to the FOV. Each of the penumbra has a different waist point along the length of the PHA body, providing different magnifications for each aperture. These waists are located 50mm, 100mm and 150mm from the front face of the PHA. One of the apertures is a half penumbra, providing a fiducial in all the neutron data collected from the system, enabling simple orientation verification for image analysis.

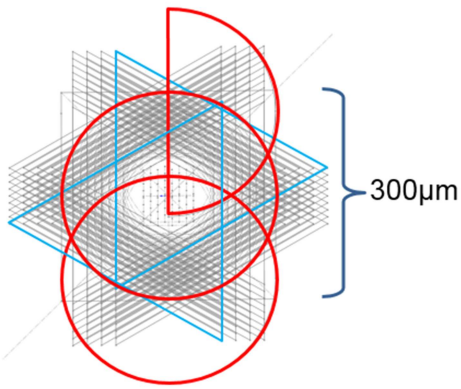

Figure 4: Layout of neutron aperture FOVs in the source plane

B. γ-ray Apertures

Figure 2 showed the layout of the 12 γ-ray penumbral apertures #1-12, as seen from the back side of the PHA. Each aperture has a field of view of 400µm and aim points in the source plane spaced on a 100µm grid, as shown in figure 5. This provides coverage of the 700µm area as required. The symmetry of the array is broken in two ways. One of the apertures is a half penumbral, and the apertures are divided between two magnifications. The size characteristics are the same as the neutron penumbral aperture, with the waist locations 50mm and 150mm from the front of the PHA. This has the effect that for the image plate recording systems, there will be an additional 12 neutron penumbral images which will aid in commissioning and alignment verification.

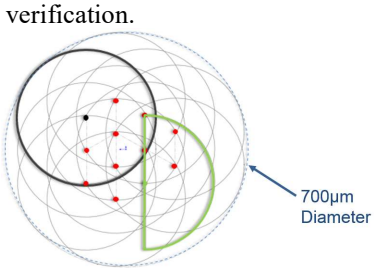

Figure 5 - Layout of γ-ray aperture FOVs in the source plane

C. X-ray Apertures

Eleven 10-µm diameter x-ray apertures in 75-µm of tantalum were added directly over the γ-ray penumbral aperture and do not influence the γ-ray or neutron images. Dual magnification of the apertures is achieved by placing 6 apertures in the foil mounted to the front of the PHA, with clearance openings for the other γ-ray apertures. The other 5 apertures are contained in a foil that is mounted to the back of the PHA, with clearance openings on the alternate holes. This technique has been used for some time on the other equatorial LOS, and provides a method to capture co-axial X-ray, γ-ray and neutron images.

D. Aperture Summary

Tables 3 and 4 provide a summary of the apertures included in this array.

E. Verification of the Design with Simulations

The penetrating nature of the particles being imaged makes linear projections inaccurate for verifying the design. While they have some value, linear projections will predict larger image sizes, spaced in closer proximity than in the actual data. Therefore, this aperture design was forward modeled given a reasonable source. The results of this analysis are shown below in Figures 6-7. This information allowed optimization of the aperture spacing and pointing

TABLE III . Summary of apertures

Type & waist location	Field of View (µm)	Front Open-ing (µm)	Waist (µm)	Z offset (mm)	Aft open-ing (µm)	Aperture ID
γ-ray, front	400	315	300	50	609	1, 2, 4, 6, 7, 9, 10, 12
γ-ray, rear	400	334	300	150	380	3, 5, 8, 11
Neutron, front	150	300	300	50	565	51
Neutron, mid	300	300	300	100	454	50
Neutron, rear	300	300	300	150	368	49
Neutron pinhole	200	15	300	-	230	13-48 & 52-87
x-ray pinhole, front	-	10	-	-	-	1, 3, 5, 7, 9, 12
x-ray pinhole, rear	-	-	-	-	10	2, 4, 6, 10, 11

TABLE IV . Image magnifications based on detector positions

Location	Image Type	Aperture type	Magnification
Port cover detector (A) 5.5m from TCC	x-ray	Pinhole	18 & 10
	Time integrated neutrons	Pinhole	18
		Penumbral	15, 13, 11
Target bay wall (B) 15.5m from TCC	Time integrated neutrons	Pinhole	52
		Penumbral	45, 39, 34
Recording systems in Switchyard 2 (C) & (D) 26m from TCC	Primary & Down-scattered Neutrons	Pinhole	89
		Penumbral	76, 66, 58
	γ-ray	Penumbral	76 & 58

to minimize the size of the recording systems required to collect the data. In addition, the simulations and experience on the other lines of sight provided confidence that sources at the edge of the FOV of the array could be collected and analyzed in spite of the distortions evident in the data, as shown in figure 8.

V. METROLOGY

All of the preceding sections describe the ideal array, and the use of image analysis and simulation to derive the data from the system. This connection and interdependent relationship cannot be overstated. To have confidence in the images reconstructed from the experiment, the actual dimensions of the apertures and placement in relationship to the target must be calculated within 2µm, in the X & Y and 250µm in Z. If the PHA is well characterized, then the data encodes the position information in the images resulting in

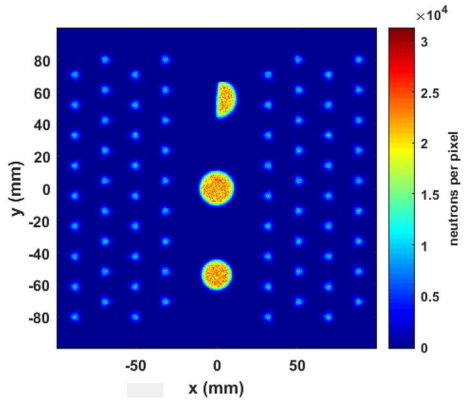

Figure 6: Simulation of neutron data, with an on axis source

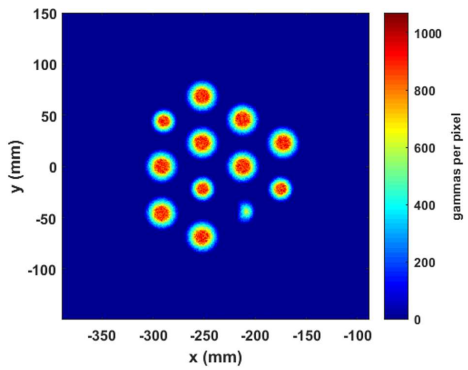

Figure 7: Simulation of γ-ray data, with an on axis source

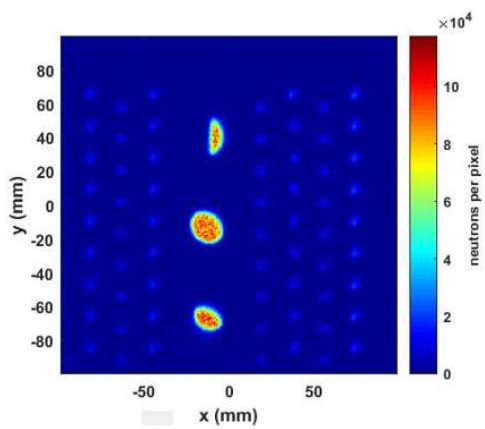

Figure 8- Simulation of neutron data, with a source positioned off axis -200μm in both X and Y.

data which is well understood. In previous PHA builds, the characterization was done via optical measurements of the features at the ends of the PHA and online characterization of the PHA at the Omega laser facility. The measurements did not provide sufficient information to understand each aperture independently due to differences in facility layout, source intensity and recording system limitations.

Metrology of this array has become a significant part of the scope required to fabricate the array. Each layer has multiple features to aid in connecting the metrology information collected from a variety of devices. The plan is to measure each layer, prior to assembly, making scans of the profile at 11 places along the length of the grooves. Once the PHA is assembled, additional scans will be made of the ends of the array, and the combination of all the data will be an as-built model of the entire aperture array, which will be used to simulate the expected images and deconvolve the images collected during experiments. The process for this work has been defined, however the actual work has yet to take place, and the exact method and results of this metrology will be published in a future paper.

VI. CONCLUSION

We have developed a new aperture array design for combined time-integrated imaging of 14.1-MeV fusion neutrons, down-scattered neutrons, γ-rays and x-rays at the National Ignition Facility. The array is the currently being manufactured and characterized and should be fielded on NIF's third nuclear imaging LOS by the end of 2018. With the addition of this LOS, NIF will have three near orthogonal neutron imaging lines of sight and its' first dedicated γ-ray imaging line of sight, which will allow significantly improved measurements of the size and shape of the fusion hot spot, cold fuel and remaining ablator.

VII. ACKNOWLEDGEMENTS

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