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LLNL-JRNL-732945

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June 12, 2017

Review of Scientific Instruments

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Citation: Review of Scientific Instruments **87**, 11D821 (2016); doi: 10.1063/1.4960314

View online: https://doi.org/10.1063/1.4960314

View Table of Contents: http://aip.scitation.org/toc/rsi/87/11

Published by the American Institute of Physics

REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 11D821 (2016)

Design of the polar neutron-imaging aperture for use at the National Ignition Facility

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(Presented 7 June 2016; received 8 June 2016; accepted 12 July 2016;
published online 15 August 2016)

The installation of a neutron imaging diagnostic with a polar view at the National Ignition Facility (NIF) required design of a new aperture, an extended pinhole array (PHA). This PHA is different from the pinhole array for the existing equatorial system due to significant changes in the alignment and recording systems. The complex set of component requirements, as well as significant space constraints in its intended location, makes the design of this aperture challenging. In addition, lessons learned from development of prior apertures mandate careful aperture metrology prior to first use. This paper discusses the PHA requirements, constraints, and the final design. The PHA design is complex due to size constraints, machining precision, assembly tolerances, and design requirements. When fully assembled, the aperture is a 15 mm × 15 mm × 200 mm tungsten and gold assembly. The PHA body is made from 2 layers of tungsten and 11 layers of gold. The gold layers include 4 layers containing penumbral openings, 4 layers containing pinholes and 3 spacer layers. In total, there are 64 individual, triangular pinholes with a field of view (FOV) of 200 μm and 6 penumbral apertures. Each pinhole is pointed to a slightly different location in the target plane, making the effective FOV of this PHA a 700 μm square in the target plane. The large FOV of the PHA reduces the alignment requirements both for the PHA and the target, allowing for alignment with a laser tracking system at NIF. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4960314]

I. INTRODUCTION

The shape of the 14.1-MeV neutron emission created in DT fusion experiments at the National Ignition Facility (NIF) is a key measurement for understanding the performance of the implosion.[1] While there is an existing Neutron Imaging System (NIS)[2,3] on the equator of the experimental chamber, understanding the three-dimensional nature of the implosions requires measurements from more than one direction, and a new system, known as NIS-NP, has been designed for the North Pole of the chamber.

Due to the penetrating nature of 14.1-MeV neutrons, the NIS and NIS-NP are thick-aperture imagers that require extended tapered apertures rather than simple pinholes. Even using gold, which has a 3.3-cm mean free path, obtaining sufficient contrast requires 20-cm thick apertures. The additional requirement for 10-μm resolution means that the apertures have high aspect ratios as well that creates narrow fields of view and require tight alignment tolerances. Moreover, manufacturing limits in creating apertures with such large aspect ratios play a defining role in the pinhole array (PHA) design. For instance, malleability and ductility are as important in the choice of gold as the aperture material as the neutron mean free path. Non-round aperture cross sections are often simpler to manufacture and are therefore preferable, even if they produce images that require reconstruction with maximum-likelihood algorithms.[2]

While most of the imaging requirements of the NIS-NP are the same as for the NIS, the location on the North Pole will require alignment using a laser tracking system, known as the Advanced Tracking Laser Alignment System (ATLAS), which is expected to position a known point on the PHA to within 30 μm of the desired position. This is significantly lower resolution than the telescope-based system used for the NIS, and the original NIS aperture design cannot be used for the NIS-NP. To mitigate this issue, the NIS-NP design requires more apertures to create a larger effective field of view than that used for NIS.

In this work, we discuss how the NIS-NP requirements and manufacturability influence the design of the array. We also describe the final design and manufacturing of the PHA as well as the metrology that is required to guarantee that the PHA is sufficiently well characterized that image reconstruction can be used to extract the source shape from the images.

II. REQUIREMENTS

Two main imaging requirements drive the design: the resolution of individual images must be 10-μm and the FOV of an individual pinhole must be 200-μm in the target plane. In addition the detector will be located 16.5 m from target chamber center (TCC) due to facility constraints. The current detector, a stack of polyethylene (n,p) converters and image plates, is limited to 20 cm by 40 cm. As the future scintillator

Note: Contributed paper, published as part of the Proceedings of the 21st Topical Conference on High-Temperature Plasma Diagnostics, Madison, Wisconsin, USA, June 2016.

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is expected to have similar resolution limits as the existing scintillator, the magnification is kept at 81, placing the front of the PHA 200 mm from TCC.

The contrast of the system drives the 20 cm length of the PHA. All the internal features are cut into gold for machinability and physics requirements. At the same time, the minimum gold layer thickness that can be handled and machined properly is 180 μm. The FOV of a single pinhole and the location of the PHA mandate the size of cut in the gold for each pinhole, 0 μm at the front and 200 μm at the back. Previous experience taught us that it is important to be able to see the features from the exterior of the PHA, so the front cut was opened to 15 μm. Each pinhole can then be projected to the recording system, defining the space required to collect the image. Due to the high aspect ratio of the individual pinholes in the PHA, the alignment of the system is critical. A single pinhole would require an alignment precision beyond the facility capability. In addition the signal collected from a single pinhole is insufficient for image reconstruction. To mitigate these issues, we use an array of pinholes with overlapping fields of view.

The number of apertures is set by the number of images that can be collected across the short dimension of the recording system, allowing for eight images, given the FOV and magnification. Due to the limit of layer thickness, and an interest in symmetry, there are also eight pinholes in the vertical dimension, making for a total array of 64 pinholes, as shown in Figure 1. Each pinhole points to a slightly different position at the target plane. The grid is asymmetric with 60 μm spacing when projected to the target plane. The rows are in line, but the columns are shifted 30 μm, Figure 2. This shift increases the effective FOV of the array to a 700 μm square at the source plane. The PHA now has an inferred axis, based on the centerline of the array which must be aligned to TCC with achievable RMS tolerance of ±125 μm in X and Y, and ±250 μm in Z. In addition, six penumbral apertures are included in this PHA to aid in determining the alignment of the system.

III. MACHINING LIMITS AND PHA DESIGN

For our purposes, an ideal neutron pinhole would be a double conical opening, with the cones coming to a very small diameter apex inside the aperture. Such double-tapered

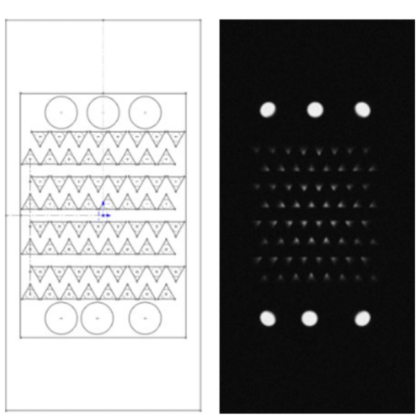

FIG. 1. Layout of data on the 20 cm by 40 cm recording system showing 64 triangular pinhole images and six penumbral images: (L) straight projection, (R) simulated data projection.

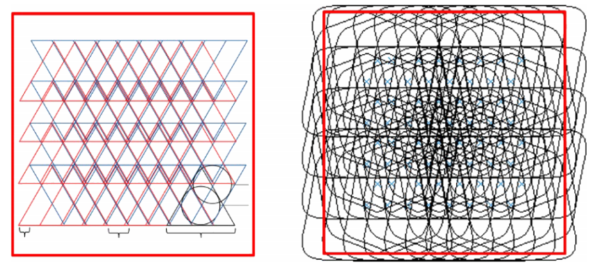

FIG. 2. Projection of pinholes on target plane, 700 μm square at image plane shown for scale in both. (L) Straight pinhole projection, (R) neutron projection.

apertures are difficult to manufacture, so we use single-tapered apertures with the narrow end of the taper closest to the source. For conical apertures, however, even a single conical taper would need to be machined from two layers of material with half of the cone on either side. The small features required for this work, 15 μm to 200 μm diameters, would require a tool bit that changes diameter as it cuts along the length, and very close to the smallest diameter, the tool will make a cut that is wider than it is deep. Since the true imaging portion of the pinhole is in that very small region, this would not produce a quality pinhole. In addition, this ideal pinhole would require features to be cut into two surfaces and then assembled into a single feature, a process that is prone to misalignments that can misshape the pinholes. To avoid these issues, we use triangular pinholes made by cutting an equilateral triangular groove on a layer and stacking the plates together with a solid layer next to the groove, forming a closed aperture.

The penumbral openings are double conical shape, providing another imaging mode.[4] They are a straight cylinder from the front face to the center, of 300 μm in diameter, and then they taper to a 500 μm diameter at the back face of the PHA. Penumbral openings have some of the same issues as described with the pinholes, but due to their larger cross section they are big enough to overcome these problems. A misalignment of 5 μm on a 300 μm opening, while not ideal, is much more tolerable than the same error on a 15 μm opening.

To create the 700 μm effective FOV, which is forgiving of misalignment, each pinhole points to a different, but known, place in the target plane. Each individual pinhole maintains the necessary high resolution. In addition, the intensity and location of the images on the recording system will provide information about the alignment of the pinhole with respect to the target, as the best aligned pinholes will produce the brightest image. This provides feedback about the actual alignment of the PHA and target.

Each of the penumbral apertures has a FOV of 300 μm, and the array of six allows for almost complete coverage of the same FOV as the smaller pinholes. Previous versions of the PHAs have been completely symmetric, which can create confusion in determining the orientation of the data. To avoid this problem, this PHA has an intentional asymmetry: one layer of penumbra openings has the center penumbra projecting back to the image plate at a slight angle, creating a permanent, easily recognizable, fiducial in the data (Fig. 3).

Previous experience with PHAs has made it clear that the PHAs will never be placed closer than the designed position.

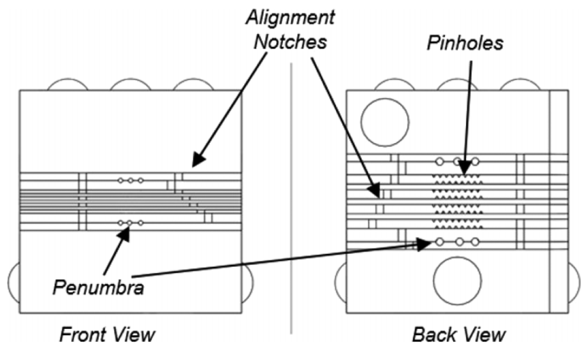

FIG. 3. View of front and back of assembled PHA.

FIG. 4. Individual gold penumbral layer, 3 grooves scribed along the length.

There may be advantages to positioning the system with the PHAs farther from TCC. Knowing this, the decision was made to have all the pinholes cross each other between the front face of the PHA and TCC. In the event of problems with alignment, or a desire to increase the FOV of the PHA, the PHA can be moved away from TCC. In order to keep the signal from the pinholes and the penumbras separate, it was decided that the penumbra would cross on the far side of TCC. This makes the opposite sides of the recording system bright for the best aligned pinhole and penumbra for any given shot.

IV. PHA FABRICATION AND METROLOGY

The simplified version of the PHA is that it is a 200 mm × 15 mm × 15 mm tungsten block, with small pinholes running the long length of it. The actual fabrication of the PHA is more complicated. It is made from 13 different layers. The outer most layers are relatively thick plates of tungsten. The inner 11 layers are thin foils of gold, as the gold can be machined with features this small, and of this tolerance, using traditional machine tools. The two outer layers of gold are 0.508 mm thick and have this single thickness along the entire length of the pinhole. The rest of the layers are cut in a wedge shape, to allow them to point to a different position in the target plane. The two penumbra layers taper from 0.651 mm to 0.885 mm. The four layers with eight pinholes on each side taper from 0.230 mm to 0.633 mm and the three spacer layers taper from 0.210 mm to 0.367 mm.

The tungsten layers are machined to a tapered shape 5.566 mm thick at the front, and 4.290 mm thick at the back face. This wedge shape makes up for the difference in height that the 11 tapered gold layers create. The tungsten layers provide the stiffness for the structure and shield much of the line of sight from neutrons that could scatter to the detector.

Previous experience mandated more visible, metrology features for the individual layers. Each layer now has a unique set of machined notches at both ends. These notches cut through the entire layer, allowing for the foil to be scanned prior to assembly, revealing the feature dimensions and variations along the length. Once assembled, the entire exterior of the PHA can be scanned, allowing calculation of the exact pointing of the individual apertures of the array, with respect to known fiducials. This calculation defines the inferred axis of the PHA and provides the nominal aim point. Additional larger metrology features were added for verification of the alignment with a coordinate measuring machine.

Many of the pinhole layers have pinholes machined on both sides with alternating orientation of the triangular apertures. While this is harder to machine, it is intentional, as the signal is distorted due to the triangular shape of the pinhole, and having pinholes with opposite orientations in close proximity helps the reconstruction of the images by creating an effective aperture with sixfold symmetry rather than threefold symmetry. In addition, the two rows of pinholes in each single layer should be aligned within the machine tolerances, as there is no assembly tolerance for the single layer.

Machining of these gold foils, Figure 4, is an engineering challenge. The size and tolerance of the features require great attention to thermal stability, datum location, assembly order, and process. Individual layers are carefully machined and measured to the same data used during assembly and inspection references at the ends. The entire pinhole must be stacked in place, and the top tungsten layer placed before any of the layers is secured. All thirteen layers are held together with ten M3 fasteners, which are tightened after all the layers are stacked and datum surfaces are aligned. After the PHA is assembled, both ends of the PHA are inspected using an optical coordinate measuring machine to tie all the indication marks of the final assembly together so that each of the pinhole and penumbra can be determined relative to the inferred axis of the PHA. The PHA will then be fully characterized through a series of shots at the Omega Laser Facility, prior to being installed at NIF.

V. CONCLUSIONS

The NIS-NP aperture design is complex due to size constraints, machining precision, assembly tolerances, and design requirements. When fully assembled, the aperture is a 15 mm × 15 mm × 200 mm tungsten and gold assembly. The PHA body is made from two layers of tungsten and eleven layers of gold. The gold layers include four layers containing penumbral openings, four layers containing pinholes, and three spacer layers. In total, there are 64 individual, triangular pinholes with a FOV of 200 μm and six penumbral pinholes with a FOV of 300 μm. Each pinhole is pointed to a slightly different location in the target plane, making the effective FOV of this PHA a 700 μm square in the target plane. The large FOV of the PHA reduces the alignment requirements for the PHA and target and allows for alignment with ATLAS. This PHA is in fabrication and will be tested at the Omega Laser Facility at the end of August 2016.

ACKNOWLEDGMENTS

This work has been performed under the auspices of the U.S. Department of Energy for NNSA Campaign 10 (Inertial Confinement Fusion) with Steve Batha as the program manager.

[1]J. Lindl *et al.*, "Review of the National Ignition Campaign 2009-2012," Phys. Plasmas **21**(2), 020501 (2014).
[2]F. E. Merrill *et al.*, "The neutron imaging diagnostic at NIF," Rev. Sci. Instrum. **83**(10), 10D317 (2012).
[3]P. Volegov *et al.*, "Neutron source reconstruction from pinhole imaging at National Ignition Facility," Rev. Sci. Instrum. **85**(2), 023508 (2014).
[4]N. Guler *et al.*, "Simultaneous usage of pinhole and penumbral apertures for imaging small scale neutron sources from inertial confinement fusion experiments," Rev. Sci. Instrum. **83**(10), 10D316 (2012).