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Collimator Design for Neutron
Imaging of Laser-Fusion Targets

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Collimator Design for Neutron Imaging of Laser-Fusion Targets

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ABSTRACT

Several "pinhole" collimator geometries for use in neutron imaging experiments have been modeled and compared. Point spread functions are shown for a cylinder, hyperbola, intersecting cones, and a five-zone approximation to the intersecting cones. Of the geometries studied, the intersecting cones appear the most promising with respect to neutron efficiency, field of view, and isoplanatism.

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I. Introduction

The spatial distribution of the DT burn within laser fusion targets is a significant issue within the laser fusion program. Our laboratory previously determined the size and shape of the reacting fuel region using alpha particle imaging techniques.¹ For Nova type targets, this imaging will not be possible because the high density fuel and pusher regions will absorb the alpha particles. For this reason we are interested in imaging with the highly penetrating 14-MeV neutrons.

To evaluate the potential of an ICF neutron "pinhole" imaging diagnostic for the Nova laser facility, we studied the effect of collimator design on image quality. A collimator (the three dimensional analogue of an optical pinhole camera) consists of a high Z material with an aperture through it, where the diameter is a function of the position along the collimator axis. For envisioned imaging experiments, the collimator would be approximately 100-mm long² and placed 500 mm from the emitting source with its aperture axis accurately aligned with the source. The detector array would be placed 100 to 200 m from the source, giving magnifications in the range of 200 to 400, and source plane resolutions of 5 to 10 μ m.

Since the beginning of this effort, several areas have been identified for study: collimator design, construction and alignment, detector design, and neutron image analysis. All of these areas have been addressed to some degree. However, this report only covers the collimator design and its consequences on the field of view, neutron efficiency, and obtainable spatial resolution. It should be realized that the design will also have bearing on the construction of the collimator. This is also considered here. The following sections include a background of the work previously completed followed by the technical details of this study.

II. Background

To analyze collimator designs it was first necessary to have codes to simulate neutron propagation from the source to the detector. Existing Monte Carlo codes (e.g., TARTNP, MORRIS) are quite sophisticated, statistically taking into account the multiple scattering undergone by each neutron as it passes through the collimator. These codes are difficult to set up for each new collimator design and time consuming to run for a sufficient number of source neutrons to get a representative distribution in the detector plane. For these reasons a new code was written based solely on neutron attenuation using the neutron mean free path of the collimator material. The latest version describes the collimator aperture with segmented second order functions. A comparison of this code with TARTNP, for collimators with small outside diameters to minimize neutron scattering showed no discernible differences. Thus, using this code, an efficient parametric study of collimator configurations was possible.

III. Collimator Geometries

A number of collimator configurations have been explored. The most promising ones, compared here, are: the cylinder, hyperbola of revolution, a pair of intersecting cones, and segmented approximations of the latter two. Figures 1 through 4 show cross sections of these geometries. The cylinder is the most obvious geometry and the easiest to construct. For these reasons it may be considered the basis for comparisons. The hyperbola and intersecting cones are studied because they have the potential for better field of view and efficiency. Segmented approximations are considered because they may prove easier to construct than the configurations where the aperture diameter varies continuously along the collimator axis.

For comparison, all collimators discussed have the same length, l , and the same aperture diameter, $2a$, at a distance, s , from the source plane. A parameter, d , is defined as the radius of the circle formed by the intersection of the source plane and the mathematical function describing the collimator (see figures 1 through 4). The d -parameter is a somewhat qualitative definition of the field of view. For point source

locations within d , good imaging can be expected. Image degradation for positions greater than d (outside the "field of view") should occur. Note that for the cylinder configuration the d -parameter is fixed by a , whereas for the other geometries the d -parameter can be varied for a given a .

The numerical values used for the calculations and plots that follow are: $l = 100$ mm, $a = 2.5$ μ m, $s = 500$ mm, $d = 10a$ and $20a$ (except for the cylinder where $d = a$). The collimator material is assumed to have a neutron mean free path of 35 mm, and the detector plane is located at $z = 200$ m (magnification of 400).

IV. Neutron Images - The Point Spread Function

The point spread function for this report is defined as the neutron intensity distribution in the image plane for an isotropic point source. As in any imaging system, the point spread function should be as narrow as possible because it is directly related to the spatial resolution that can be achieved. Spatial resolution, defined in the classical sense, is the minimum separation of two point sources that appear distinct in the image. Enhanced spatial resolution can be achieved by post-imaging analysis, particularly by deconvolving the image and the separately determined point spread function. Deconvolution is most easily performed when the point spread function is isoplanatic; that is, depends only on the difference between the coordinates in the source and image planes. This implies that isoplanatic point spread functions have the same shape independent of the source position, a potential issue for non-planar imaging devices such as a collimator.

The point spread function has been calculated and plotted for the collimator configurations described earlier. The plots shown in figures 5 through 8 are for the cylinder, hyperbola, intersecting cones and a five-zone segmented approximation to the intersecting cones for $d = 10a$. Within each figure the plots correspond to different source positions from $x = 0$ (on axis) to 50- μ m off axis. Contour levels are drawn at intensity intervals of 0.1 of the peak signal. For each contour plot, there is an intensity plot for $y = 0$, i.e., a radial intensity profile through the center of the image.

Because the neutron mean free path is comparable to the collimator length, the detector plane point spread function changes slowly as the point source is moved off axis. This can be seen by comparing the plots in figures 5 through 8. The shape change is most pronounced for the cylinder configuration and least for the intersecting cones. To quantify this observation, the integrated neutron intensity over one resolution element³ centered at the geometrical image point, normalized to its on axis value, is plotted in figure 9 for three of the collimator configurations. The more rapid decay in detector plane neutrons distorts the image, an undesirable characteristic that is clearly minimized with the intersecting cone geometry. The curves in figure 9 behave similarly when the smooth collimator functions are replaced by their respective five-zone segmented approximations.

V. Neutron Images - Two Point Resolution

In this study, only classical two point resolution has been addressed. Figures 10 and 11 show images of two point sources spaced slightly more than one aperture diameter apart ($\frac{6}{5} \cdot 2a$) for the hyperbola and intersecting cones, respectively. For source positions less than a ($=10a$), the points are slightly better resolved by the hyperbola configuration. This can be attributed to the steeper sides of its point spread function (compare the on-axis point spread functions in figures 6 and 7). Note, however, that the symmetry and constancy of the images are much better for the intersecting cones than for the hyperbola configuration for source positions 25 to 50 μm off axis. This is a direct consequence of the higher degree of isoplanatism.

VI. Scaling

Scaling of collimator dimensions transverse to the aperture axis results in a similar scaling for the field of view and the detector plane resolution. The signal-to-background ratio scales as the square of the aperture diameter since the signal scales as the square of the aperture diameter and the background is related to the collimator length (i.e., larger apertures lead to increased signals, but decreased resolution).

Changing the collimator length affects the signal-to-background in an exponential way. Typically, longer collimators of a particular axial profile have better signal-to-background ratios and sharper signal cut-off at the edge of the field of view.

Translation of the detector plane parallel to the aperture axis does not change the shape of the point spread function or the number of source neutrons reaching a particular resolution element. It does provide magnification adjustment so that the resolution element size can be optimally matched to the elemental detector size.

Changes in the d -parameter affect the general shape of the collimator and therefore changes the point spread function. As d decreases, the field of view over which good imaging occurs gets smaller and the edge of the point spread function increases in slope. The cylinder configuration is the limiting case for all other geometries as $d \rightarrow a$.

Finally, a change in the source plane position has a varying effect depending on the specific geometry of the collimator. Translation of the source toward the collimator has no effect on the d -parameter for the cylinder; decreases for hyperbola; and becomes ill defined for the intersecting cones. In all cases, however, the number of source neutrons reaching the detector plane and the system magnification increases. The overall effect is a change in the point spread function.

VII. Conclusions

The study of collimator configurations presented here is a first step toward reaching the optimum design for future Nova neutron imaging experiments. Of the several collimator geometries that were modeled and compared, the pair of intersecting cones appears to be the most promising with respect to neutron efficiency, field of view, and isoplanatism. Although it did not have the best classical resolution (but not far off), the prospects for enhanced resolution by deconvolution are particularly attractive.

To simplify construction of a particular collimator geometry, it was shown that segmented approximations suffer little in comparison to the performance of their mathematically smooth counterparts. The greater the number of segments, the better the point spread function becomes.

Further work on the neutron imaging should address enhanced reconstruction of the source from the image data and prior knowledge of the point spread function of the imaging system.

References

1. N. M. Ceglio and L. W. Coleman, "Spatially Resolved α Emission from Laser Fusion Targets," Phys. Rev. Lett. 39, 20 (1977).
2. The mean free path of a 14-MeV neutron in copper is approximately 40 mm and in tungsten is approximately 31 mm.
3. A resolution element in the image plane is defined as the area of the minimum collimator aperture (diameter is $2a$) multiplied by the magnification of the imaging system.

Figure 1 - Cylinder configuration.

Figure 2 - Hyperbola of revolution configuration.

Figure 3 - Pair of intersecting cones configuration.

Figure 4 - Five-zone segmented approximation to pair of intersecting cones.

Figure 5 - Point spread functions for the cylinder ($d = a$). The upper left hand illustration shows image plane intensity contours for an on axis ($0 \mu\text{m}$) point source. Succeeding image plane contours correspond to point sources at increasing off axis positions ($5 \mu\text{m}$, $10 \mu\text{m}$. . . $50 \mu\text{m}$ off axis).

Figure 6 - Point spread functions for the hyperbola ($d = 10a$). Off axis intensity contours as described in figure 5.

Figure 7 - Point spread functions for the intersecting cones ($d = 10a$). Off axis intensity contours as described in figure 5.

Figure 8 - Point spread functions for the five-zone segmented approximation to the intersecting cones ($d = 10a$). Off axis intensity contours as described in figure 5.

Figure 9 - Relative degree of isoplanatism for three collimators. The flatter response shown by the intersecting cones is the most desirable of these curves. The curves behave similarly when the smooth collimator functions are replaced by their respective five-zone segmented approximations.

Figure 10 - Two point resolution - hyperbola ($d = 10a$). Distance between point sources is $6 \mu m$.

Figure 11 - Two point resolution - intersecting cones ($d = 10a$). Distance between point sources is $6 \mu\text{m}$.