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Abstract

We are currently designing a 10-μm resolution neutron penumbral-aperture microscope to diagnose high-convergence targets at the Nova laser facility. To achieve such high resolution, the new microscope will require substantial improvements in three areas. First, we have designed thick penumbral apertures with extremely sharp cutoffs over a useful (≈100 μm) field of view; fabrication of such apertures appears feasible using gold electroplating techniques. Second, the limited field of view and required close proximity of the aperture to the target (2 cm) necessitates a durable mounting and alignment system with ±25 μm accuracy. Finally, a neutron detector containing 160,000 scintillator elements is required; readout and optimization of this large array are outstanding issues.

Introduction

Penumbral-aperture imaging is a coded-aperture imaging technique that has been applied to sources of x-rays[1], and neutrons[2]. Conceptually, it is similar to pinhole imaging, with the essential difference that the aperture must be larger than the source. The image produced consists of a uniformly bright region surrounded by a partially-illuminated penumbra that encodes information about the spatial intensity distribution of the source. The coded image can be reconstructed through deconvolution.

We have begun work to extend neutron penumbral-aperture imaging down to two-point resolutions as small as 10 μm. Our efforts are preliminary, and here we report on progress made to date. Substantial progress has been made in the design and fabrication of thick apertures for neutron penumbral-aperture microscope (NPAM) applications. A novel form of clad-scintillator array will be used as a detector; two schemes are under study to read out the required large array. The components of the high-resolution NPAM must be aligned to within ±25 μm of the source; a scheme using the diffraction generated by a laser-illuminated disk is being studied. Imaging performance of the present system design has been tested by computer simulation with encouraging results. Fabrication of the improved NPAM is planned to begin in the latter half of 1990.

Thick-Aperture Design and Fabrication

High-resolution penumbral imaging of weak sources of penetrating radiation requires an aperture with a particular set of characteristics. First, adequate contrast requires use of an aperture several mean-free paths thick, often a thickness of many centimeters. (The total mean free path of 14-MeV neutrons in gold is 3.4 cm, for example.) Note that the aperture material provides contrast by deflecting the neutrons, principally through elastic scattering, into a solid angle that is very large compared to that subtended by the detector. Next, the aperture point-spread function (PSF) must have a sufficiently sharp cutoff. In addition, to obtain an image of a relatively weak source with an acceptable signal-to-noise ratio requires that the aperture be quite close to the source. Finally, penumbral imaging requires numerical reconstruction of a coded image to obtain an estimate of the source. The computational difficulty of the reconstruction is vastly reduced through use of an isoplanatic aperture and linear reconstruction techniques. Therefore, imaging system magnification must be reasonably uniform across a useful field of view (FOV).

Simple conical apertures have unacceptable PSFs if the vertex of the cone must be moved away from the source plane to provide sufficient isoplanaticity across an acceptable FOV. Better performance is available with apertures having a parabolic taper, but only when the aperture can be placed sufficiently far from the source. Our current design, the IRC taper, makes use of an aperture taper in which the radius of curvature varies inversely with distance from the source plane.[3] To achieve 10-μm resolution, we plan to use a 1-mm diam 6-cm thick gold aperture mounted with the front face 2 cm from the target.

Aperture fabrication involves three steps. First, mandrels are ground to the desired aperture shape from a brass cylinder using a numerically-controlled precision lathe. Next, the mandrel is straightened and characterized. Finally, the mandrel is electroplated with gold to a diameter of 0.64 cm, and the brass removed from the gold by chemical etching. Initial attempts to fabricate an IRC-tapered aperture have been encouraging. While the mandrels are being straightened, their diameter is measured as a function of axial position with an accuracy $\leq \pm 5\mu m$, see Fig. 1. When four mandrels from a single batch are compared to the design specification, we see two systematic errors. A small "cut off" error at the large end of the aperture, and a more serious oscillation at the small end. The oscillation is probably a transient associated with the start of the cut, and may be reduced by offsetting the machine programming. The problem should also be less severe in future designs that use larger-diameter apertures. Despite these errors, the present fabrication efforts are sufficient to achieve resolutions close to 10 μm.

Detector Design

The signal-to-noise ratio advantage of penumbral imaging over pinhole imaging is obtained mainly from increased solid angle. To obtain an acceptable image from a weak source, a large aperture is required (1 mm diameter) and the detector must count neutrons with high efficiency. To obtain high ($\approx$ 20 %) counting efficiency, we will use an array of plastic 10-cm-long scintillator elements; such arrays are now commercially available.[4] Each element of the array is clad to provide a total-internal-reflection interface and painted with an extra-mural absorber, resulting in good optical coupling from end to end without optical cross talk between elements.

Minimum system magnification is determined by the desired resolution, Δs, and the scintillator-element size, Δd, from the Nyquist theorem, $M > 2\Delta d/\Delta s$. For our high-resolution imaging it is desirable, therefore, to use the smallest element size possible; otherwise the detector must be made physically large and located a great distance from the neutron source. Previously we made use of elements with $\Delta d = 2$ mm, a size that minimizes the effects of recoil proton cross talk between elements. In our new design we plan to use elements with $\Delta d \leq$ 1 mm. To limit recoil-proton cross talk between elements, the elements will be bonded together with a thin ($\leq$100 μm) layer of an epoxy-based high-Z paint. Experiments to characterize small (8-cm square) sample arrays will begin in late 1990.

The present design for our high-resolution system calls for a 400×400 array of 1-mm-diam scintillator elements, see Fig. 2, to be operated at a magnification in the range 250—300. Two schemes have been proposed for readout of the 160,000 elements in the array. In the first scheme, the array would be imaged by a very fast ($f < 1$) optic onto a small (4 cm) microchannel-plate image-intensifier tube, and the amplified image recorded using film or a CCD camera. The optical imaging can be fairly coarse, needing only to resolve the 1-mm detector elements, and mild geometric distortion could be removed computationally. However, such an optic will have to be large (>40-cm diam), and probably aspherical, and therefore very expensive. Another option is to "proximity focus" the light emitted from the array onto an array of solid-state detectors. We will begin evaluation of these arrays (which are a proprietary commercial product) in the near future.

System Alignment

In the present design, the aperture must be mounted so that its front face is 2 cm from the center of the Nova target chamber; to achieve a magnification of 280, the detector must be back approximately 17 m. A mounting and alignment system must both position and point the thick aperture along an axis defined by the centers of the target chamber and neutron detector. Alignment errors cause a translation of the coded image on the detector; the detector must therefore be made oversize at additional expense to compensate. Also, the coded aperture has a limited FOV, with reduced resolution as the source region moves away from the aperture axis. For the aperture and detector described above, it is necessary to achieve an alignment accuracy of $\leq \pm 25$ µm referred to the source plane. The following is an alignment scheme currently being developed.

To align the aperture a straight-line reference (SLR) is first established between the target position and the detector. A disk is aligned at the target position and illuminated with a collimated laser beam. Behind the disk and along the beam will be a Poisson line, a diffraction pattern suitable for precision alignment.[5] The beam is adjusted to put the Poisson line onto the center of the detector, and a telescope is aligned along the SLR. Next, the disk is removed from chamber center and the aperture moved into place. The aperture has a disk on its rear face that has been centered on the aperture axis. When the aperture is illuminated by the previously adjusted laser beam, another Poisson line is produced, and the aperture translated until the line is collinear with the SLR. Alignment is completed by pointing the aperture using auto-collimation. The telescope, already aligned to the SLR, simultaneously views and projects an internal reticle. The projected image reflects from a mirror mounted on the rear surface of the aperture and prealigned to be precisely perpendicular to the aperture axis. The aperture pointing is then adjusted so that the reflected image is coincident with the reticle.

The aperture mounting and alignment system is complicated by the mechanical environment within the Nova target chamber. Roughly a kJ of energy will be incident on the system each time the Nova laser is fired, producing a large force impulse and material ablation. In order to survive, the aperture and its precision-alignment mechanics must be protected by a blast shield. The entire system must also be quite compact, as it is nominally required to fit within a cone having a 9° half angle. For example, to be positioned 2 cm from chamber center, the aperture and blast shield together must have a diameter ≤ 6.3 mm.

Simulated System Performance

Simulation of coded-image formation requires several steps. First, PSFs are generated for source points at various radial displacements from the aperture axis. When the PSFs are deconvolved with a reference function, we find acceptable resolution and isoplanaticity across a 150-μm FOV.[3] To generate a simulated coded image, a hypothetical source distribution is superpositioned with the spatially-variant PSFs, and noise added based upon a specified neutron yield. Deconvolution of the simulated coded images confirms satisfactory imaging of small circular and elliptical source regions.

To generate a PSF, a large set of rays are traced from the source point to the detector plane. The trace calculates the amount of material intersected, and simple exponential attenuation using the total neutron mean free path determines the transmission of each ray. This model assumes that all scattering events within the aperture result in particle loss; actually, the neutrons are largely scattered into some solid angle. In our geometry, the average scattering solid angle is much larger than that occupied by the detector, so that very few of the scattered neutrons (<0.4%) hit the detector.

Images are deconvolved in the Fourier transform domain with a parametric Wiener filter, $\left[A_{ref}\left(1 + k/|A_{ref}|^2\right)\right]^{-1}$, where A_{ref} is the transform of an idealized penumbral-aperture PSF, the rectangle function $\Pi(\rho/D)$, with a diameter D equal to that of the IRC on-axis PSF. The filter suppresses spatial frequencies close to the zeroes of A_{ref}, but the parameter k is kept small (2×10^{-4}) to avoid blurring the reconstruction.

The IRC aperture can provide 10-μm resolution across a 150-μm-diam FOV. Performance is excellent close to the axis; for displacements ≤40 μm the full width at half maximum (FWHM) resolution is ≤5 μm. At the edge of the useful FOV, a displacement of 75 μm, the resolution deteriorates to 10 μm. Magnification variations, a measure of the isoplanaticity, are <6% across the FOV.

Simulated coded images were generated for two hypothetical two-dimensional Gaussian source distributions: circular with a FWHM diameter of 17 μm yielding 10^{11} neutrons; and elliptical, 8 × 15 μm, yielding 5×10^{10} neutrons; see Fig. 3. The deconvolution parameter k was adjusted to optimize the image resolution versus signal-to-noise ratio (SNR). The circular source was imaged at a resolution of 12 μm; an ensemble of such images gives an average FWHM of 19 μm with a peak SNR of 13. The smaller, weaker elliptical source was best imaged at a resolution of 9 μm; an ensemble average gives dimensions of 12 × 18 μm with a SNR of 8.

Summary

We have a tentative design for a NPAM providing two-point resolutions as small as 10 μm for targets yielding $\leq 10^{11}$ neutrons. The IRC thick-aperture design has been analyzed computationally, and provides the necessary resolution across a sufficient FOV; initial fabrication results are encouraging. A 10-cm long array of 400 × 400 1-mm-diam clad scintillators will be used as a detector; recoil-proton cross talk between elements will be eliminated with a high-Z bonding paint. The light produced by the array will be read out either by optical coupling and intensification, or by proximity-focused solid-state arrays. System alignment requires translating and pointing the thick aperture to within ±25 μm of the target, and will make use of Poisson-line diffraction patterns. The imaging of small test sources has been simulated computationally; the results demonstrate acceptable resolution and SNR.

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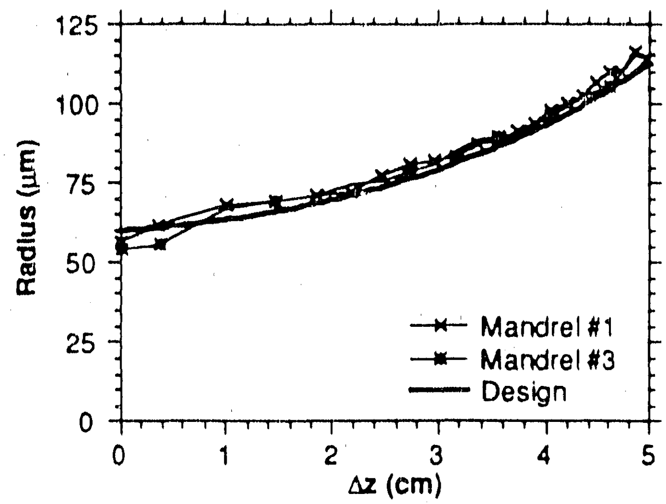
Figure Captions

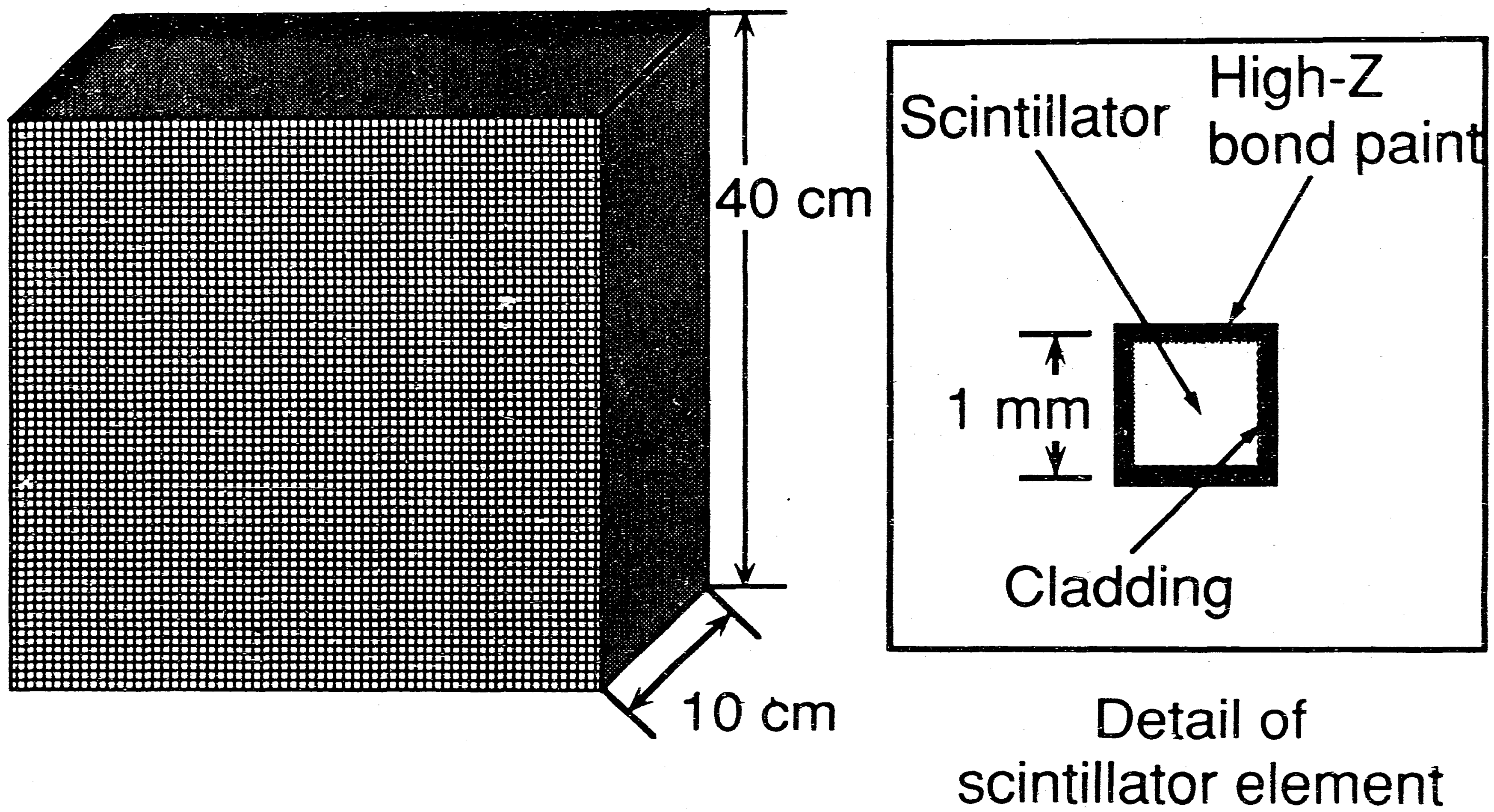
Fig. 1. Recent efforts to fabricate the thick IRC aperture are encouraging.

Fig. 2. The detector will be a 400 × 400 array of clad scintillator elements.

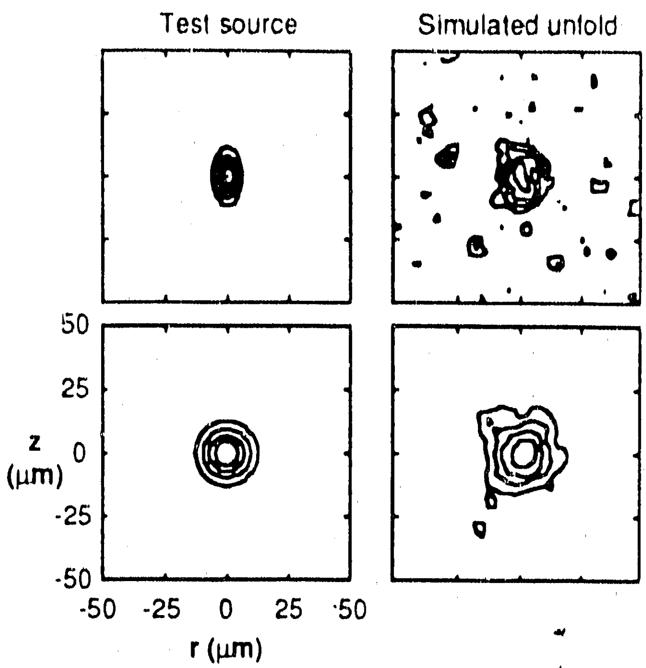
Fig. 3. Simulations of penumbral-aperture imaging show satisfactory performance with small, weak test sources. The contours indicate 20, 40, 60, and 80 percent of the peak intensity.



D. Ress, et al. — Figure 1



D. Ress, et al. — Figure 2



D. Ress, et al. — Figure 3.

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