A LARGE-FORMAT IMAGING OPTICS SYSTEM FOR FAST NEUTRON RADIOGRAPHY*

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Abstract

As part of the ongoing development of fast neutron imaging technology for national security applications at LLNL, a large-format imaging optics system is being designed and built. The system will be used to acquire radiographic images of heavily-shielded low-Z objects irradiated by ~ 10 MeV neutrons and is expected to have an ultimate spatial resolution ~ 1 mm (FWHM). It is comprised of a 65 cm x 65 cm plastic scintillator (*e.g.* BC-408), an aluminized front-surface turning mirror and a fast (~ f/1.25) optical lens coupled to a CCD camera body with a cryo-cooled, back-illuminated 4096 x 4096 (15 µm) pixel sensor. The lens and camera were developed and purchased from vendors and system integration is being done at LLNL. A description of the overall system and its projected performance characteristics shall be presented.

INTRODUCTION

Fast neutron imaging is a powerful non-destructive evaluation (NDE) technique that uses the penetrability of fast neutrons to image details in low-Z materials that are heavily shielded by high-density, high-Z materials. Such configurations pose a challenge for x-ray imaging since the high-Z surrounding "hardens" a typical bremsstrahlung x-ray spectrum from an electron stopping target, and it is the lower energy photons that are lost that are needed to image the low Z materials inside.

While neutron imaging is a promising technique, a major challenge to using it is finding a sufficiently intense source of neutrons to allow reasonable short imaging times (on the order of minutes) while still being compact and relatively inexpensive. While nuclear reactors can provide copious intensities of thermal and higher energy neutrons in planar source configurations, and have been used to demonstrate the efficacy of the approach, they are hardly compact and inexpensive enough to be practical as a source for most NDE applications.

In pursuing neutron imaging, LLNL has been working on the development of a compact, inexpensive, and deployable approach to such a machine. The neutron source would be based on accelerator-driven neutron production, where deuterium ions would impinge on a transmission deuterium gas cell to produce 10 MeV neutrons. To take advantage of being able to focus the beam down to less than 1.5 mm in diameter, various windowless gas cell concepts have been explored and developed to produce a bright "point" neutron source to facilitate high resolution imaging.

Downstream of the gas cell, the largely forward-directed neutron beam would be further defined by high-attenuating collimators before it passes through the object under inspection. A shadow radiograph would then be produced as the neutrons interact with a fast-neutron-sensitive scintillator that would produce light, and the light would be collected in a state-of-the-are large format imaging optics system comprised of the scintillator, a low-mass turning mirror to keep the imaging camera out of the neutron beam path, a fast-optic large-diameter lens, and a 4096 by 4096 pixel CCD camera, all in a light-tight enclosure. A schematic of the layout is shown in Figure 1.

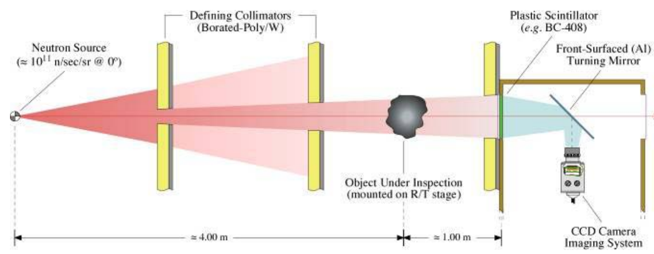

Figure 1: A layout for doing fast neutron imaging, showing the neutron source as the dot on the left, and the neutron beam as it is collimated before creating a shadow radiograph on a scintillator on the right. The light is then turned with a mirror and focused onto the CCD camera using a wide-aperture fast lens.

PROOF OF CONCEPT

The use of quasi-monoenergetic 10 MeV neutrons has been shown to produce high-quality neutron radiographs of test objects. Experiments done at the Ohio University Accelerator Lab (OUAL) have demonstrated the efficacy of the technique for imaging heavily shielded low-Z materials [1]. Over 25 different test objects have been imaged, and the results have met or exceeded expectations. As an example, Figure 2 shows an image of a LiD block that was shielded by 2" of depleted uranium. The image not only clearly shows test holes drilled in the LiD, it also shows the ragged edges of the material where pieces broke off during fabrication.

The images obtained at OUAL were made on a prototype imaging optics system that used a commercial fast lens and was able to view a 30 cm x 30 cm scintillation screen. The images were captured on a liquid nitrogen cooled camera with a 1024 x 1024 (24 micron) pixel back-thinned CCD chip which was coupled to a high speed *f* /1.0 commercial photographic lens. This system worked very well and laid the groundwork for designing a larger, more efficient imaging system to allow imaging larger objects.

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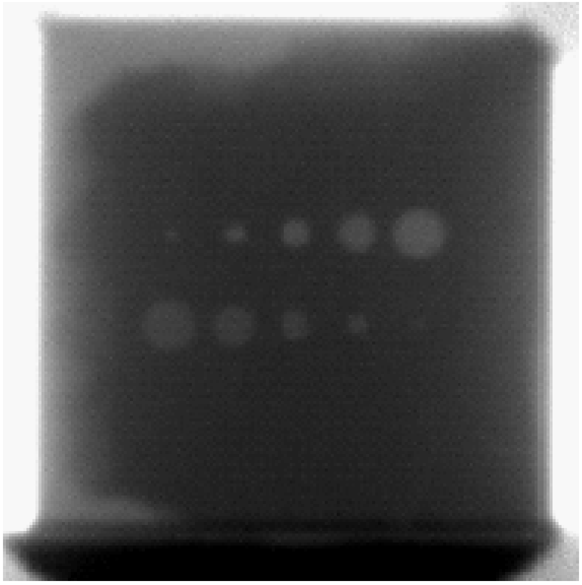

Figure 2: A fast neutron radiograph of 1” thick LiD block shielded by 2” of depleted uranium. The image shows not only the test holes drilled down to cubic mm void size, but also showed where material around the edges cracked off during machining.

DEVELOPMENT EFFORTS

Developing a new system to capture images from a 65 cm x 65 cm scintillator screen while maintaining a spatial resolution comparable to that of our prototype system at OUAL posed appreciable technical challenges. The new system must also maintain high light collection efficiency in order to minimize exposure times for the objects under inspection. This made the lens design for focusing light from the scintillator onto the CCD chip especially challenging.

Scintillator

Prototyping work done at OUAL evaluated 2 and 4 cm thick samples of three different scintillator materials (BC-430, -400, and -408) from Saint-Gobain (formerly Bicron) as well as a thinner (2.4 mm) ZnS screen. From this work, BC-400 and BC-408 appear best suited for our application. Based on the (n,p) mean free path (MFP) for 10 MeV neutrons, detection efficiencies of approximately 10% should be attainable using 2-3 cm thick scintillators. A comparison of BC-400 and BC-408 are shown in Figure 3.

Lens Assembly

Capturing light from the scintillator and focusing it onto the CCD imaging chip will be done with a 4” diameter entrance aperture ~ f/1.25 lens. The lens assembly design and build was performed by Optics 1, Inc. It consists of nine individual lens elements, as shown if Figure 4.

Property	BC-400[1]	BC-408[1]
Peak λ (nm)	~ 423	~ 425
Average λ (nm)	~ 444	~ 431
Neutron sensitivity[2] (nerg/(n,p))	~ 90.8	~ 94.8
Decay time (ns)	~ 2.4	~ 2.1
Resolution[3] (mm)	~ 0.98	~ 0.98
(n,p) MFP[4] (cm)	~ 20.0	~ 20.0
Ave. λ MFP (cm)	~ 160	~ 210

[1] Polyvinyltoluene (PVT) based (H/C ~ 1.1/1), ρ = 1.032 g/cc, n = 1.58
[2] Average light evolved (nerg) per 10 MeV (n,p) reaction in scintillator
[3] Diameter enclosing 90% of light evolved from 10 MeV (n,p) reaction
[4] Mean free path (MFP) for 10 MeV (n,p) reactions in PVT (ENDFB6)

Figure 3: Table comparing select properties of (n,p) scintillators from Saint-Gobain. Both scintillators should produce approximately 10% detection efficiencies for 10 MeV neutrons for thicknesses of 2-3 cm.

To maximize light collection efficiency from the scintillator, the lens transmission wavelength was optimized for 425 nm. The specified scintillator-to-lens spacing is 1038.7 mm, and the lens-to-CCD chip spacing is 12.4 mm. A picture of the delivered lens is shown in Figure 5.

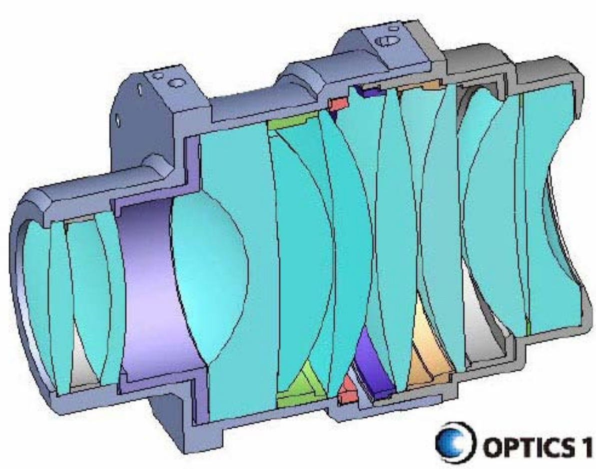

Figure 4: Drawing showing the 9 lens elements in the assembly. The entrance aperture is on the left.

CCD Camera

The CCD camera that will be used to capture the images was custom built by Spectral Instruments based on their 4-port cryo-cooled 1100 Series. It has a 4096x4096 (15 micron) pixel back-illuminated 4-port scientific-grade-1

Figure 5: A photo of the finished lens assembly designed and built by Optics 1, Inc. shown with the shutter (left). CCD sensor made by Fairchild Semiconductor.

which is flat to +/- 30 microns. The camera is cryogenically cooled to operate in the -95°C to -110°C temperature range to minimize thermal noise and to allow long image acquisition times, on the order of tens of minutes. The camera entrance window is coated to allow maximum light transmission at 425 nm. A picture of the purchased camera is shown in Figure 6.

Figure 6: A photo of the 4096 x 4096 (15 micron) pixel cryogenically-cooled 1100 Series CCD camera built by Spectral Instruments. The nom. 6” diameter entrance aperture on the right will be close-coupled to the lens.

SYSTEM INTEGRATION

Work is presently underway to design and build a system to integrate the above components. The scintillator will be placed in a specialized frame that allows for different scintillators of varying thickness to be used. A thin turning mirror will be used to deflect light from the scintillator to the lens/camera which allows the camera to avoid direct exposure to the intense neutron beam, which can cause neutron-induced flashes (so called “neutron stars”) on the image and possible electronics damage. Having a thin mirror is an important consideration in the design since we also want to minimize neutron scatter into the camera. The camera and lens assembly will be mounted on an adjustable mount that will allow multiple degrees of tip, tilt, and displacement adjustment. Finally, the entire system will be surrounded by a light-tight enclosure. A conceptual drawing of the overall system is shown if Figure 7.

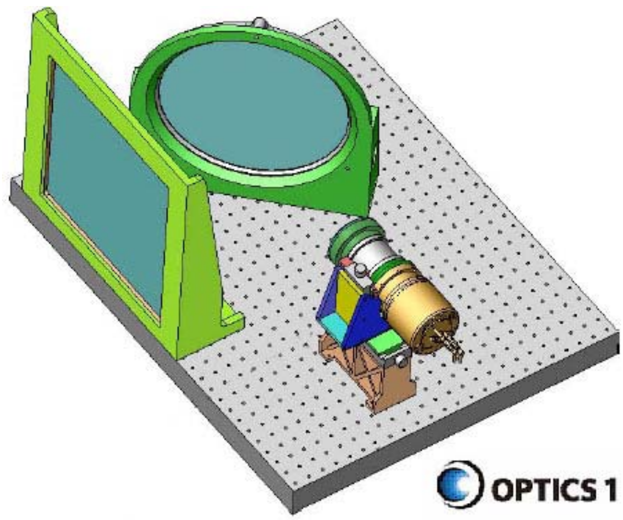

Figure 7: Conceptual drawing of the integrated imaging system showing the camera/lens assembly, turning mirror, and scintillator in its holder. Not shown is the light tight enclosure surrounding the components.

CONCLUSION

Development work is continuing toward building a state-of-the-art fast neutron imaging optics system as a new NDE diagnostic tool. Having purchased a fast lens assembly and CCD camera from industry, efforts are now focused on designing and building the mechanical components and integrating the system together. We expect to begin evaluating the system in early 2008.

AKNOWLEDGEMENTS

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REFERENCES

[1] J. M. Hall, et al., “High-energy Neutron Imaging Development at LLNL,” Proc. of the 8th World Conf. on Neutron Radiography, Gaithersburg, MD, May 2007.

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