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THERMAL AND COLD NEUTRON COMPUTED TOMOGRAPHY AT THE LOS ALAMOS NEUTRON SCATTERING CENTER USING AN AMORPHOUS SILICON DETECTOR ARRAY

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INTRODUCTION

The use of the EG&G-Heimann RTM 128 [1] or dpiX FS20 [2] amorphous silicon (a-Si) detector array for thermal neutron radiography/computed tomography has proven to be a quick and efficient means of producing high quality digital radiographic images. The resolution, although not as good as film, is about 750 μm with the RTM and 127 μm with the dpiX array with a dynamic range in excess of 2800. In many respects using an amorphous silicon detector is an improvement over other techniques such as imaging with a CCD camera, using a storage phosphor plate or film radiography. Unlike a CCD camera, which is highly susceptible to radiation damage, a-Si detectors can be placed in the beam directly behind the object under examination and do not require any special optics or turning mirrors. The amorphous silicon detector also allows enough data to be acquired to construct a digital image in just a few seconds (minimum gate time 40 ms) whereas film or storage plate exposures can take many minutes and then need to be digitized with a scanner. The flat panel can therefore acquire a complete 3D computed tomography data set in just a few tens of minutes. While a-Si detectors have been proposed for use in imaging neutron beams [3], this is the first reported implementation of such a detector for neutron imaging.

EQUIPMENT AND FACILITY

The neutron beam used for the imaging tests is located on Flight Path 11a in building ER-2 at the LANSCE (Los Alamos Neutron Scattering Center) spallation source [4]. To produce neutrons at LANSCE, a tungsten target is bombarded by a 70 μamp , 800 MeV pulsed proton beam (250 ns pulse width at 20 Hertz rate). An intense shower of neutrons are produced in the tungsten target and are scattered into moderators where they

Figure 1. Schematic diagram of experimental setup.

interact with hydrogen, losing momentum, and then travel down flight tubes to the various experimental beam stations. A 20 m, straight, super mirror beam guide was used to guide the neutrons from the moderator to the experimental cave at the end of flight path. (See Figure 1) The beam at the end of the guide has a 6 cm x 6 cm cross-section and a divergence of less than one degree. Depending on the moderator temperature, the average energy of the neutrons can be from subthermal to above 0.03 eV.

The detector used for the initial tests was an EG&G-Heimann Electronics demonstration model amorphous silicon detector system called the RTM 128. The RTM 128 is a 96 mm x 96 mm square amorphous silicon image sensing photodiode array consisting of 128 x 128 pixels with a pitch of 750 μm . The usable dynamic range was on the order of 14 bits and approximately 10% of the pixels on this early prototype array were either non functional or were partially functional. After no radiation damage was noted to the RTM 128 (after > 15 hours of exposure to the beam), a larger 20 x 25 cm (1536 by 1920 pixels) and finer pitch 127 μm array from dpiX was used for most subsequent imaging. This detector had a usable dynamic range of 2800 (>11 bits) and had only 1.5% non-functional pixels.

PRELIMINARY MEASUREMENTS

Since no thermal neutron radiography had ever been done on a flight path at LANSCE, and indeed, no neutron radiography had been done at a large spallation source, there was concern that the gamma flash from the proton-tungsten target interaction might be very intense rendering thermal radiography difficult if not impossible. Therefore, a number of preliminary measurements including the measurement of neutron flux, gamma flux, scatter and beam uniformity needed to be made. To measure the gamma flux, a

Radcal Corp. model 9010 gamma counter was placed in front of the beam tube such that it covered beam cross section. The flux ($3.2 \mu\text{R/s}$) was found to be at least an order of magnitude lower than that found in most thermal neutron beams at reactors.

In addition to measuring the gamma flux directly, a thin, 0.0508 cm thick, Cadmium foil was inserted in front of half of the RTM 128 for a 2.8 s exposure. The side of the image with the Cd sheet placed in front of it was attenuated by a factor of 2.72 compared to the image side. The area outside the beam was down by a factor of 3.74 compared to the exposed image. Later, ASTM (E 545-91) standard blocks were used to infer the beam quality.

To measure the flux of neutrons, the same thin Cadmium sheet (as above) was placed in front of the beam, covering the whole beam cross-section, in order to attenuate the beam because the expected flux exceeded the counting rate of a large area single channel helium three neutron detector (six ^3He tubes in a $8.9\text{t} \times 23.5\text{w} \times 35.5\text{h}$ cm poly block) [5]. This detector placed directly behind the Cadmium sheet was then gated on 10 times for 10 s and the results averaged. The average number of counts per second from the 36 cm^2 beam was $39,160 \pm 200$ at a proton current of about $70 \pm 2 \mu\text{A}$. Since the attenuation factor of the cadmium was about 382 and the detector efficiency was 18% the neutron beam flux is about 2.1×10^6 [neutrons/ $\text{cm}^2\text{-s}$]. This compares favorably with the neutron flux in the cave at the now decommissioned (1993) Omega West reactor, 6×10^5 n/ $\text{cm}^2\text{-s}$ (at a l/d of 190) where neutron radiography was previously performed at Los Alamos [6].

Given the beam apertures and distances back to the moderator, the l/d ratio was calculated to be approximately 43. An exact l/d is not a trivial calculation due to low angle reflections of neutrons in the beam guide and the uncertainty in the neutron spectrum. A beam divergence of less than one percent is expected for subthermal

Figure 2. The image on the left is of the beam (as measured with the RTM128 and Bicron 704 scintillator) with no test object. The two black intersecting lines represent the row and column presented in the smoothed line plot in the right hand image. Other spots and lines, in the image on the left, are defective or weak pixels or lines.

neutrons.

A measure of the scatter at the detector and at other areas was made by counting the number of hits found in the detector pixels that were not exposed directly to the beam and by moving the ^3He detector to other locations in the cave. The scatter was equal to about 5% of beam flux used to image our samples and will be reduced by replacing the beam stop in the experimental cave.

To determine beam uniformity, the a-Si detector and later, R type film (with a Gd converter foil) were exposed to the beam to produce images that were evaluated for uniformity. The beam appears to be fairly uniform (see figure 2 (left)). Data from the 42nd row and column are shown as solid and dashed lines in Figure 2 (right). (The 42nd row and column were chosen because they bisected the beam cross-section.) The line plots show a fairly even distribution across both axes of the detector. The variation is about 8%.

IMAGING TESTS

Due to limited beam availability we were only able to take a few images with the a-Si detectors. The images taken were mostly of a 3/8" stainless steel bolt threaded through a brass nut and of a 1/4 inch thick stainless steel test piece. The test piece had several holes and slots machined half way through the thickness of it. Centered in each of the holes and slots smaller holes and slots were machined completely through the thickness of the piece.

The exposure lengths for the images varied between 2.8 and 5.6 seconds. In some cases, as many as 50 exposures were taken and the data was averaged to get better statistics. However, the quality of the multiple exposure images was not much better than a single frame exposure. On the left in Figure 3 is an image taken with a Bicron 704 ^6Li doped ZnS scintillator to be compared with the image on the right taken with a Rarex scintillator.

Figure 3. On the left is an image of the beam with the left hand side of the detector covered with a 0.05 cm thick Cd foil using the Bicron 704 scintillator. Notice that the part of the image that is covered is almost as dark as the area around the beam where there is little or no neutron flux. On the right is an image of the same bolt and test piece but using a Rarex (Gadolinium Oxysulfide doped with Terbium) scintillator.

The images taken with the Bicorn type 704 scintillator were significantly sharper and had more contrast than the Rarex scintillator, however the Bicorn scintillator did show radiation damage after 12 hours of exposure to the beam. The image of the test piece in Figure 3 shows the test piece held in place next to a stainless steel bolt. The image shows several holes and the slot milled partially through its thickness. However, it doesn't show the smaller holes that are milled completely through it. This is at least partially due to the fact that the holes and slots (which go completely through the thickness of the material) were smaller than the pixels of the RTM 128.

To produce typical CT images (such as the one shown in Figure 4) a rotation stage was incremented every 5 degrees and an image recorded using the dpiX array. Image acquisition and transfer time was about 7 seconds per image, however it took about an hour, or more, to obtain a data set in this manner manually. Due to software problems, the data sets were not optimized for dynamic range and therefore do not indicate what can be achieved with this beam line. Because of the sparse data set, a number of artifacts are noted, but interestingly the typical rind artifact due to beam hardening is not readily apparent.

DISCUSSION

The preliminary imaging tests conducted with the amorphous silicon detectors at LANSCE have been quite successful. It has been verified that thermal neutron imaging can be performed using a beam guide with no beam scrapers or collimators and achieves images with resolutions on the order of the detector pixel size ($127\text{ }\mu\text{m}$) or better.

A natural extension of this imaging technique is cone beam neutron computed tomography (CT) [7]. We plan to produce more CT images using an automated system during the next beam cycle.

In the near future we hope to test the a-Si detector's imaging capabilities with a

Figure 4. A 38 mm diameter brass test block (left) and a reconstructed image (right) from 72 views of the brass block using a parallel beam reconstruction code. Two of the holes were filled with epoxy and appear lighter than the non-filled holes. The dpiX array was used to collect the image data for reconstruction.

reactor neutron beam to compare results with the data from LANSCE. It would also be interesting to gate the detector for short periods during the beam pulse cycle to select precise neutron energies. This would allow us to look above and below the Bragg edges of certain materials.

CONCLUSION

With a limited amount of beam time we were able to characterize several beam properties as well as produce images of test samples. The resolution of the images was limited only by the pixel size of the detector. Imaging with the a-Si detectors has been shown to produce quality digital images in a short amount of time with minimal setup, making it an attractive detector for many applications. No degradation in the detector was noticed during the collection of these images, however the scintillator material did suffer some discoloration and subsequent efficiency degradation.

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