Design and evaluation of a unique weighted-sum-based Anger camera

Matthew W. Seals

University of Tennessee, Knoxville, mseals2@vols.utk.edu

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Design and evaluation of a unique weighted-sum-based Anger camera

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Matthew W. Seals
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Abstract

Anger camera imaging technology has become widely popular for neutron diffraction imaging due to recent shortages in Helium-3 (He-3). Research into neutron diffraction optimized Anger camera by the Oak Ridge National Laboratory (ORNL) detectors group has provided an alternative to He-3 Tube-based detectors with a high-resolution Anger camera. However, the cost of these high-resolution Anger camera technology can make it less attractive than He-3 tubes when a large Field of View (FOV) is desired. Currently, there is a need for a lower-cost alternative to this high-resolution Anger camera. Further applications for Anger camera have become of interest with the advent of high-flux Deuterium-Tritium (D-T) gas lab-based neutron generators. Implications of utilizing high-sensitivity Anger camera technology in use with high-flux lab-based neutron generators could lead to the development of a lab-based neutron diffraction instrument.

A novel low-cost weighted-sum-based Anger-logic architecture optimized for neutron diffraction applications was developed targeting performance metrics like those demonstrated by more traditional resistor-network-based Discretized Positioning Circuits (DPC). The weighted-sum architecture proved capable of achieving 6mm ~ 4mm resolution as would be typical of resistor-network-based DPCs. The weighted-sum architecture was then applied to a monolithic Anger camera design. This design provided a weighted-summing board interfaced to an H8500 Multi-Anode Photomultiplier Tube (MAPMT) through circuitry to correct for anode gain nonuniformity. The outputs of the weighted-summing board were processed through custom-designed sampling and digital signal processing (DSP) hardware to calculate the position of incident photons on the MAPMT. Correction of anode gain nonuniformity provides
for accurate pulse shape discrimination of light pulses incident on the MAPMT resultant from scintillation events.

A monolithic high-resolution Anger camera developed by the ORNL detectors group was applied to a newly developed high-flux D-T gas lab-based neutron generator by the Phoenix Nuclear instrument company. A single crystal pyrolytic graphite panel was used to acquire a neutron diffraction rocking curve. The high sensitivity and gamma rejection capability of the high-resolution Anger camera facilitated improved Signal to Noise Ratio (SNR) given the low neutron flux and high gamma-ray background.
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Chapter I. Introduction
Neutron diffraction application for non-destructive mechanical testing

Neutron diffraction has become an indispensable tool for the characterization of mechanical properties of materials in a non-destructive manner. The scattering effect that occurs between the neutron and the atomic lattice of the material under test reveals information about the mechanical state of the atomic lattice [1]. This scattering effect is known to be Bragg scattering where the incident neutron upon an atomic lattice will diffract at an angle, $\theta$, in proportion to the spacing of the atomic lattice, $d$, and the de Broglie wavelength of the neutron, $\lambda$ [1, 2].

$$\lambda = 2dsin\theta$$ (1)

A relativistic neutron has velocity $v$, a wavelength $\lambda$, with energy $E$.

$$\lambda = \frac{h}{mv}; \quad E = \frac{h^2}{2m\lambda^2}$$ (2)

Where $h$ is plank’s constant and $m$ is the mass of the neutron. The objective function of neutron diffraction is the lattice spacing of atomic planes within the material. To relate the angle $\theta$, of the diffracted neutrons to the lattice spacing $d$, the wavelength of the neutrons incident on the sample must be controlled for. The beam incident on the sample is either monochromatic [3] or pulsed. Pulsed beams are used for selection of specific neutron wavelengths by taking advantage of the relationship between the velocity of the neutron and it’s de Broglie wavelength. This velocity selective method is termed time-of-flight[4].

The core of a diffraction instrument is comprised of a neutron source (either pulsed or monochromatic), a sample positioning stage system, and a spatially resolved neutron sensitive
detector. With the use of slits and other neutron optics the incoming beam $I_0$, and diffracted beam $I_d$ are used to select specific gauge volumes withing the sample material[1]. The resultant diffraction pattern of scattered neutrons at the detector takes on the form of a bright vertical band as depicted in figure 1 (Appendix: Chapter I Figures and Tables, pg. 60). The band will shift horizontally or broaden in response to mechanical changes and deformation of the sample including residual mechanical effects of applied loading in and heating/cooling cycles[5, 6].

Figure 2 (Appendix: Chapter I Figures and Tables, pg. 61) illustrates the basic concept of deformation of the atomic lattice to the shift in the Bragg angle. The deformation of the lattice in the longitudinal direction resulted in a shift in the d-spacing of 3A. The resultant shift in $2\theta$ is from $14.33^\circ$ to $57.29^\circ$ can be found by calculating the respective d-spacings into eq. 1 for a 4A neutron. An illustration of a working beam line at the High Flux Isotope Reactor (HFIR), CG-1A, is depicted by figure 3 (Appendix: Chapter I Figures and Tables, pg. 62) with a diffraction experiment underway using a prototype Anger camera looking for a diffraction signal from a germanium powder sample.

**State of the art of neutron diffraction detection**

There are several methods by which neutrons can be detected and spatially resolved to a point of incidence [7]. The most suitable method deployed is largely dependent on the specific application. For use in radiography, it would likely be necessary to employ a typical CMOS(Complementary Metal Oxide Semiconductor) flat panel detector providing high resolution and high field of view[8]. For applications in neutron diffraction imaging, however; there exists ‘counting’ detectors which are optimized for diffraction detection[9].
detectors are focused on providing key functionality critical to detecting scattered neutrons in environments hosting diffraction instruments. Quite typically, a neutron diffraction signal resultant from a sample under test will be many orders of magnitude smaller than the incident beam. There also exists, within spallation and reactor-based diffraction instruments, a significantly high background level of gamma rays. These gamma rays are undesirable and only contributes to poor signal to noise ratio[10]. The challenges associated with high background gamma are typically overcome with the use of a pulse-shape discrimination method[11]. Pulse shape discrimination is a feature that can only be found in counting neutron detectors. Unlike flat-panel CMOS detectors, counting detectors evaluate each incident particle individually in terms of its electronic pulse response when incident with the detector. Discrimination seeks to assign a likelihood to each interaction of being from either a neutron or a gamma. The features used to parameterize this likelihood include the height and width of the resultant electronic pulse. The features, once quantified and compared to experimentally gathered spectrums, can be used to assign a likelihood to either accept the data as a neutron, or reject the data as a gamma. Counting detectors employ the use of either a neutron-sensitive scintillator coupled photomultiplier tube array, or a helium-3 tube array to detect and spatially resolve the position of an incident neutron.

Helium-3 (He-3) based detectors have largely spear-headed the field of neutron diffraction imaging becoming a main staple of many neutron diffraction beamlines including beamlines at the High Flux Isotope Reactor (HFIR) and the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL)[12]. These detectors employ a stacked array of He-3 charged tubes, illustrated by figure 4 (Appendix: Chapter I Figures and Tables, pg. 63), with a
single thin wire positioned in the center of each tube and traversing the entire length. This wire is electrically charged to a high positive voltage. The pressurized he-3 captures a thermal neutron and undergoes a nuclear reaction producing a free triton and proton ions. These resultant particles collide with the pressurized gas in the tube producing freeing electrons which drift towards the highly positively charged wire[13, 14].

The electrical current pulled to the wire travels the length of the wire to both ends of the tube being split at the position on the wire closest to the nuclear reaction as depicted in figure 5 (Appendix: Chapter I Figures and Tables, pg. 63). Both ends of the wire feed into read-out electronics which convert current from the tube to a voltage pulse useful for data acquisition. The magnitude of the two pulses from the wire provides the point of incidence along the length of the tube. Tubes stacked into a vertical array will provide a point of incidence between tubes. With the position of incidence along the tube, and the vertical position of the tube known, it is possible to assign the point of incidence to a cartesian mapping. He-3 based detectors suffer from several notable limitations which have spurred research into further alternatives. Most notably, the reliance on He-3 to repair or replace detector tubes has come to the forefront of the search for more sustainable alternatives given past shortages of He-3[15].

Looking to alternatives to he-3 based detectors have piqued interest in designs that employ the use of off-the-shelf photomultiplier tubes (PMTs) as an alternative. Unlike He-3 tubes, PMTs do not rely on a steady supply of He-3 gas for manufacture and repair. Instead, PMTs rely on neutron sensitive scintillators to produce light in the near-UV spectrum when a neutron is incident upon them[14]. Resultant light from the scintillator then causes a photo-electric reaction. This reaction, illustrated in figure 6 (Appendix: Chapter I Figures and Tables,
pg. 64), produces an output current pulse which can be measured by connected instrumentation. PMTs are vacuum tube devices containing highly negatively charged electrodes built internally which generate photoelectrons[6, 9, 14]. The front face of the device contains a photocathode behind a transparent glass window. Photons that pass the window generate photoelectrons when incident on the photocathode. Resultant photoelectrons accelerate further into the device to electrodes termed “dynodes”. Because of the high negative charge of the dynodes, any incident electrons upon them will produce further secondary photoelectrons. This multiplication of further photoelectrons occurs at each dynode in a cascade until finally, the electrons are collected into a photoanode. The photoanode will produce a measurable electrical current in proportion to the magnitude and duration of the light pulse the PMT was exposed to. Typically, these devices output a photo gain on the order of $10^6$ electrons per photon[6].

PMTs provide a highly sensitive neutron detection mechanism within neutron diffraction instruments that provide all the necessary features of He-3 based detectors while addressing a suitable replacement in the face of He-3 shortages. However, a PMT alone cannot provide spatial information about the point of incidence of the neutron, only that the neutron was incident on that PMT. For spatially resolved measurements, PMTs must be stacked into an array to resolve neutrons between the PMTs to a cartesian position. For these measurements there exists multi-anode PMTs (MAPMTs)[6] which integrate many individual PMTs into a single monolithic device. The individual PMTs within the MAPMT are arranged in an n-by-n fashion such that, for instance, 64 PMTs are arranged in an 8-by-8 array for the Hamamatsu H8500 MAPMT. Each PMT in the device is given its own independent output from the other PMTs in
the array such that for 64 individual PMTs, 64 individual outputs are available. Each PMT in the array is analogous to a ‘pixel’ with an associated physical size taking up a square region on the face of the MAPMT. MAPMTs coupled to neutron-sensitive scintillators are used with associated read-out electronics to find the position of incident neutrons on the scintillator. These spatially resolved MAPMT-based devices are termed Anger camera and are currently of extreme interest in the neutron diffraction community as replacements of he-3 based spatially resolved neutron detection systems[16].

**State of the art for anger-logic-based neutron detectors**

Anger logic is a method by which the position of incidence of a particle upon a scintillator can be determined[17]. Detectors based upon Anger logic, termed Anger camera, are counting detectors popularly used in the field of neutron diffraction for detection of scattered neutrons. Diffraction instruments such as TOPAZ[18], and MANDI[19] at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) are designed around Anger camera. Anger camera provides high sensitivity with electronically implemented pulse shape discrimination to improve gamma rejection capability[10]. In addition to meeting these requirements needed for diffraction experiments at a spallation source, Anger camera is not dependent upon he-3.

Traditionally, Anger camera has been designed around a resistor network acting as a discretized positioning circuit (DPC), illustrated in figure 7 (Appendix: Chapter I Figures and Tables, pg. 65), for an n-by-n MAPMT[20, 21]. The resistor network behaves as a charge divider with four outputs one at each “corner” of the resistor network. Each of the outputs are fed into
transconductance amplifiers producing four analog voltages. The positional information from
the incident neutron on the scintillator is encoded into the magnitude of the four analog
signals. The position of the point of incidence on the scintillator can be calculated for the four
output signals $V_y^+$, $V_y^-$, $V_x^+$, $V_x^-$ by the following:

$$Y = \frac{V_y^+ - V_y^-}{V_y^+ + V_y^- + V_x^+ + V_x^-}$$  \hspace{1cm} (3)

$$X = \frac{V_x^+ - V_x^-}{V_y^+ + V_y^- + V_x^+ + V_x^-}$$  \hspace{1cm} (4)

The DPC is essentially an analog read-out scheme that condenses any number of ‘N’
input channels from the MAPMT down to four outputs. This scheme can be expected to provide
2mm ~ 6mm resolution for a 64-channel Hamamatsu H8500 MAPMT. This scheme has the
advantage of providing simple low-cost electronics with a constant of four outputs to be
digitally processed regardless of the number of tubes in the MAPMT. Although this scheme is
low-cost and simple, it suffers from inherent complications due to resistor value tolerances in
the DPC. Further, this design does not allow for the use of pulse-shape based gamma
discrimination. To estimate identity of the originating particle that resulted in a scintillation
event, the height and width of the resultant pulse must be compared against a threshold for
what might constitute a neutron pulse versus a gamma pulse. Complications arise since
MAPMTs, due to stochastic effects in the manufacturing process, do not exhibit consistent
photo-gain between anodes. This anode gain non-uniformity must be corrected for before
applying pulse shape discrimination. As the outputs of the MAPMT act as high-impedance photo-controlled current sources, applying correction electronics with a low-impedance output to the DPC will result in a loss of function. This design then becomes non-ideal for applications where pulse shape-based gamma rejection schemes are necessary to increase the Signal-to-Noise Ratio (SNR).

Higher resolution read-out schemes have since been developed and deployed for use at beamlines at SNS for the aforementioned TOPAZ, and MANDI diffraction instruments. These detectors find the position of a neutron by summing the rows and columns of the MAPMT. Gaussian fitting is then performed for the row and column sums such that the point of incidence of the neutron on the scintillator is estimated to be at the point where the gaussian mean of the row sums and the gaussian mean of the column sums intersect ($\mu_X,\mu_Y$). This scheme provides an improved resolution on the order 0.5mm ~ 1mm. Unlike the constant four outputs of the lower resolution schemes, this scheme produces $2\sqrt{N}$ outputs for $N$ inputs which all require sampling and digital conversion. To correct for anode, gain non-uniformity this system employs an array of preamplifiers with sized feed-back resistors to normalize the gain across the MAPMT. Given the gain across the MAPMT is consistent post-correction it then follows that it is possible to accurately perform pulse shape discrimination on individual pulses resultant from scintillation events. Figure 9 (Appendix: Chapter I Figures and Tables, pg. 66) illustrates one of the most recent of these detectors. Although the high-resolution scheme provides many desirable advantages, it comes at a cost of electronics overhead and greater overall cost to manufacture. Given that the high-resolution system encodes the position into $2\sqrt{N}$ outputs for any given $N$ inputs the associated signal processing electronics also scales at
\[2\sqrt{N}.\] Low resolution Anger camera schemes produce four outputs regardless of \(N\); therefore, signal processing electronics remain constant.

In the face of an inconsistent supply stream of he-3, Anger camera has filled a niche for some diffraction instruments becoming an excellent alternative to he-3 based detectors in some cases. Each diffraction instrument is designed with a unique type of experiment in mind. However, not all instruments require high resolution to operate effectively for their intended purpose; although, these same instruments may require a large detector area. Using higher resolution Anger cameras in a large area array could come at a cost that makes he-3 based detectors the more attractive option. This does not help to relieve the dependance of diffraction instruments on he-3. There is currently a gap that exists within the state-of-the-art for a low-resolution, low-cost Anger camera capable of filtering gammas through pulse-shape discrimination.

**Motivations**

There is growing interest utilizing the concept of a lab-based neutron diffraction instrument developed using a lab-based neutron generator in place of a spallation or reactor-based source. It is widely accepted that due to the required flux, neutron diffraction instruments must be based around a spallation or reactor neutron source. Recently, there has been critical developments into high-yield lab-based Deuterium-Tritium (DT) gas neutron generators. These generators can generate approximately \(10^{13}\) neutrons per second. Compare this with spallation and reactor sources capable of yielding \(10^{14} \sim 10^{17}\) neutrons per second[22].


Anger camera has become the targeted imaging technology to leverage for lab-based diffraction instruments utilizing such high-yield lab-based neutron sources where it affords high sensitivity, high spatial resolution, and a compact form factor. Additionally, the Anger camera can be designed in a 121mm x 300mm package weighing less than ten pounds. Image data transfer is easily facilitated by Anger camera over a remote TCP connection requiring the camera to operate in a monolithic manner independent of the need for any supporting electronics aside from a PC.

The motivation to introduce Anger camera technology to neutron diffraction stems from past shortages of helium-3 and inconsistent availability[15]. Traditional architecture of Anger camera utilizing a resistor-based discretized positioning circuit does not lend itself to a device capable of applying a pulse shape discrimination method to filter gammas[16, 17, 23]. The detectors group at ORNL has made tremendous advancements into the field of neutron-diffraction optimized Anger camera capable of high resolution. These devices have found a great deal of success at the SNS for various diffraction instruments[16, 23]. The technology has proven itself; however, the cost to deploy a detector array utilizing only Anger camera for a large field of view may be prohibitive as to make He3 the more cost-effective option. It should also be made noted, that a diffraction instrument does not always require a great deal of resolution. This problem exists due to a gap in the state of the art of Anger camera technology. A critical need exists in the field of neutron diffraction for an Anger camera capable of resolution comparable to classic resistor network based DPC designs optimized for diffraction applications.
Parallel motivation exists for a new architecture for Anger camera for studies into a lab-based diffraction instrument. One major disadvantage of the Anger camera developed by ORNL is its use of silicon-based photomultipliers (SiPMs). When overexposed to a large flux of neutrons these SiPMs begin to incur damage resulting in loss of image capability[24]. An ideal camera would utilize more traditional vacuum tube style multi-anode photomultiplier tubes as these devices are hardened against overexposure. Due to the nature of the high-flux lab-based source targeted for development of a lab-based neutron diffraction instrument shielding the camera against over exposure represents a challenge. A low-cost neutron-sensitive large-area Anger camera utilizing MAPMTs would prove ideal for this application.
References


15. *Helium-3 Shortage: Supply, Demand, and Options for Congress (R41419)*.


Chapter II. Imaging Based Detector with Efficient Scintillators for Neutron Diffraction Measurements

This chapter is a slightly revised version of a paper with the same title currently under review for submission in 2022 to a targeted journal by Matthew W. Seals, Stephen B. Puplampu, Dayakar Penumadu, Richard A. Riedel, Jeffery R. Bunn, and Christopher M. Fancher.
Abstract
Recent Anger camera developments have drawn attention in the field of neutron diffraction in search of neutron sensitive detectors with high spatial resolution, a high degree of sensitivity, and efficient gamma discrimination ability. Traditionally, Helium-3 based detectors have dominated the field of neutron diffraction imaging; however, these detectors typically exhibit poor spatial resolution. A prototype neutron sensitive large area Anger camera developed by the SNS Detectors Group at Oak Ridge National Laboratory (ORNL) has demonstrated sub-millimeter spatial resolution. To evaluate the potential benefits of employing large area Anger camera detectors in place of helium-3 based detectors a series of diffraction experiments were performed at the high flux isotope reactor (HFIR) at ORNL. Suitable shielding for operation in a high background gamma environment was developed. Measurements were carried out with an Anger camera on iron, Inconel, and tungsten powder diffraction samples to observe the signature diffraction patterns they produce when exposed to monochromatic neutrons. Measurements also aimed at estimating instrument resolution for potential residual stress measurements. Results were promising and provide the groundwork for operation in limited space environments in combination with compact neutron sources.

Introduction

Anger camera, or gamma camera, was first realized by Hal Anger for detection of gamma rays in the mid 1950’s [1, 2]. Since the original design concept was introduced, evolution and novel improvements have brought the Anger camera new regard in the field of neutron diffraction. Interest in use of this detector is due to its high sensitivity and gamma discrimination capabilities [3-5]. Neutron diffraction facilities are designed around high flux sources which
introduce a large background of gamma rays into the testing environment, presenting a unique challenge for detection of the weak signals produced by neutron diffraction. Because of this high gamma-to-neutron ratio, the entirety of the diffraction signal can be engulfed in the background gamma noise. Gammas incident on the detector, can generate false positive neutron interactions. Ideally, a detector used for diffraction applications would reject all gamma interactions, while counting each incident neutron. Currently, no technology exists capable of meeting these exact requirements, however, recent advancements in detector technology have made them very efficient at neutron detection and gamma rejection.

Traditionally, linear position sensitive helium 3-tube based detectors have been used to fulfil this role as they provide a high degree of sensitivity along with gamma discrimination capabilities; however, these detectors have a very limited spatial resolution and material is rare and not readily available [6-12]. Recent developments have made the large area neutron sensitive Anger camera a strong alternative to helium-3 based detectors offering comparable gamma discrimination capability in addition to sub-millimeter resolution and high sensitivity. The compact nature of this detector makes it ideal for use in conjunction with compact neutron sources for operation in limited space environments to carry out rapid material characterization and residual stress measurements. The Anger camera employed in the diffraction experiments described herein uses a 2mm thick enriched $Li^6$ glass (GS20) covering four 8x8 Silicon Photo Multiplier arrays (SiPMs) for a field of view of 100.88mm square. The GS20 scintillator is optically coupled to a 3.5mm glass spacer which is optically coupled to the SiPMs. The purpose of the glass spacer is to allow for the light cone produced from the scintillator to expand across the gaps in the SiPM array. When a neutron is incident on the scintillator a light cone is
generated which will activate a channel, or channels, on the SiPM array. The electrical current produced by the SiPM array is then interpreted into a Cartesian coordinate pair related to the original position of the neutron-scintillator interaction. This is achieved by dividing the charge into a series of electrical signals which contain the coordinates of the interaction encoded into their magnitude. When these electrical signals are converted from analog to digital the digital values are used to back-calculate the interaction position on an FPGA-based digital signal processor or AROC (Anger Camera Read Out Circuit). Gamma discrimination is performed by analyzing the pulse characteristics of these signals. The general shape these signals will take on will be the sum of a fast and slow decay, by looking at the width and height of the generated pulse it is possible to characterize the pulse in terms of the particle type that it was resulted from. This detector was attached to a custom fixture at beam line HB2B of the High Flux Isotope Reactor at Oak Ridge National Laboratory for use in a series of diffraction experiments using powder samples of tungsten, iron, and Inconel contained in cylindrical aluminum sample containers. These same experiments were repeated using the original helium-3 based detector of the Neutron Residual Stress Mapping Facility (NRSF2) instrument installed at that beam line [13].

Neutron diffraction experiments rely on an elastic Bragg scattering interaction to infer information about the atomic lattice spacing in an engineering material. Conventionally, diffraction studies are carried out on materials exhibiting a lattice with long range order. For a monochromatic neutron beam of wavelength $\lambda$, the scattering angle $\theta$ is related to the interplaner distance ($d$-spacing) by the following relation:
Knowing the neutron wavelength and scattering angle recorded by the detector, d-spacing is determined and lattice strains induced by external factors such as temperature changes or mechanical loading can be tracked to characterize the investigated material on a micromechanical scale.

**Materials and Methods**

**NRSF2 Instrument Description**

The incident neutron beam has a highest flux of $3 \times 10^7$ n/cm$^2$/s with wavelengths, selected by use of a bent silicon crystal monochromator, ranging from 1 to 2.7 Å. Dimensions of the incident neutron beam, which are defined by a slit system, can have width of 0.3 – 5 mm and height of 0.3 – 20 mm. The instrument detector captures $2\theta$ scattering angles from 70° to 110°.

**Installation of Anger Camera**

The NRSF2 detector chamber was modified with an additional mounting bracket to receive a prototype neutron sensitive large area Anger camera. The bracket positioned the detector at the height of scattering sample and the incident neutron beam slit. A pivot at the base of the bracket allowed the camera to change orientation in the diffraction plane to point at the gage volume of the diffracting sample. Since it was not feasible to build shielding along the entirety of the diffracted beam path, a two-component solution to prevent background neutrons from interacting with the detector was implemented. The two-piece shielding system was constructed from 9.5 mm thick ABS plastic panels and comprised two “snout” sections: a 280 mm long, tapered section with a 12.3 mm x 12.3 mm opening attached to the facing of the
Anger camera, and a 254 mm long section with a 323 mm x 323 mm base plate and a 35.6 mm x 35.6 mm opening facing the sample. The sample-facing opening was closed by a plate with a slit roughly the width and height of the sample being measured only allowing neutrons that were diffracted from the desired gauge volume of the sample to enter the double snout system and reach the Anger camera detector. Schematics of the camera mounted on the bracket and shielding system as well as actual setup are shown in Error! Reference source not found.0 (Appendix: Chapter II Figures and Tables, pg. 67).

Initial diffraction data was collected from reference powder samples used for calibration of the NRSF2 instrument at the beginning of each cycle. Single peaks were measured for Body Centered Cubic Iron, Germanium, Nickel, and Inconel powder samples. Count time for each measurement was 60 seconds. To determine detector resolution, a 2θ sweep was carried out while diffracting from the Inconel powder sample over a 4° range in ~0.007° steps. Integration of Anger camera and NRSF2 software allowed for automated image capture and detector shift throughout the sweep.

Results
The data format of the Anger camera is a 512x512 UTF-8 encoded 2-D array of 32-bit integers where each element of the array corresponds to the number of neutrons that were captured by the corresponding pixel. The camera captures neutrons for a user-specified duration of time, after which the resulting array is passed to a host PC. The raw data is decoded by the host and saved in plain-text format for analysis later. The raw pixel data is normalized by the following:
\[ I_{\text{norm}} = \frac{I - I_{\text{dark}}}{I_{\text{flood}} - I_{\text{dark}}} \]  

Where, \( I_{\text{norm}} \), is the resultant normalized 2-D array resultant from the original image \((I)\), the darkfield image, \( I_{\text{dark}} \), and the flood image \( I_{\text{flood}} \). Dark-field and Open-beam images are captured in duration for the times of interest: 60 seconds, 300 seconds, 600 seconds, and 1200 seconds. Dark field images are produced by collecting an image with the detector in place with the neutron beam shutter closed leaving only detector artifacts and background noise in the resultant image. Flood images are gathered by placing an empty sample container in the beam path with the neutron shutter open allowing the detector to count neutrons. The normalized 2-D array is then saved as a TIFF image using OpenCV module for python. The bright streak that can be observed in the TIFF image in 11(a) illustrates the presence of a neutron diffraction peak from an Inconel sample. The resultant histogram from the integration of the acquired image is shown in 11(b).

The vertical integration of the image produces a histogram, \( H \), as a 1-D array of values derived from the summation of each column of pixels in the normalized image, \( I_{\text{norm}} \), of size \((U, V)\) comprised of pixel values \( I_{\text{norm}}[u, v] \). The histogram of size \( U \) is calculated by:

\[ H[u] = \sum_{v=0}^{V} I[u, v] \quad \text{Where} \quad u \in [0, U] \]  

Once the histogram is calculated by (3), the data is now a 1-D array of 512 values, \( C \), where the index of the array, \( l \), is the channel number, and the value at that index, \( c_l \), is directly proportional to the neutrons collected on that channel. The neutron peak is considered the portion of the array, \( C \), where the height of the array “spikes” positively from the average value.
of the array. The channels containing the peak can be extracted from the rest of the array by first finding the index of the channel where the peak begins, \( i_1 \), and the index of the channel where the peak ends, \( i_2 \).

Finding the \( i_1 \), and \( i_2 \) is performed programmatically by taking the average of \( C, C_{avg} \), and iterating over the array, \( C \), starting from index 0 until the first value, \( c_i \), is found that is greater than \( C_{avg} \). This value is assigned to \( i_1 \) where it is considered the lower limit of the peak. The iteration continues onward until the index is reached at which \( C \) falls back below \( C_{avg} \), this index is assigned to \( i_2 \). It is accepted that \( i_1 \), and \( i_2 \) are the limits of a peak if they satisfy \( i_2 - i_1 > 15 \). This relation helps to prevent false positives. The subset of \( C \) containing the peak on the interval \([i_1, i_2]\) is fed into a least-squares fitting algorithm provided by the Scipy python package where it produces a best-fit model of the peak that it was presented with. This data is used to extract the Full-Width-Half-Max (FWHM) from the peak and to determine the exact channel that the peak is centered on.

The histogram on the right featured in figure 12 (Appendix: Chapter II Figures and Tables, pg. 68) shows two peaks captured from an Inconel (311) sample with the camera at \( 2\theta = 91.5^\circ \). The diffraction peaks are displayed with respect to the height and the location on the detector facing. The width of the diffraction peak is taken as the full-width-at-half-max (FWHM) as shown in figure 13 (Appendix: Chapter II Figures and Tables, pg. 69). This is found by taking the height of the diffraction peak, \( H[x_{max}] \), where \( H \) is the 1-D array of peak data. Finding the FWHM begins with finding the two points: \( H[x_1] \), and \( H[x_2] \) in the 1D data array.
$H$, that exists closest to half the max height, $H[x_{\text{max}}]/2$. The indices, $x_1$ and $x_2$, can be used to find the FWHM by simple subtraction: $FWHM = x_2 - x_1$.

Iron, Germanium, and Nickle powder samples were placed in the beam path for 60, 300, 600, and 1200 seconds each resulting in four collected diffraction patterns for each sample. The raw peak heights were collected as a function of time to observe the linear growth the maximum peak height for three different scatterers. Nickle provided the fastest growing peak and the brightest initial peak with iron following second and finally germanium. The final collection performed for 1200 seconds for these three samples is depicted in figure 14 (Appendix: Chapter II Figures and Tables, pg. 70). The maximum peak height for all samples at all times is depicted in figure 15 (Appendix: Chapter II Figures and Tables, pg. 71).

Discussion

Diffraction peaks were selected for $2\theta$ values as close to 90° as possible; for quantification of these measurements, curvature was neglected and, subsequent to normalization, raw intensity was obtained by vertical image integration. The raw peaks gathered for the various materials at various exposure times are analyzed in figure 15 (Appendix: Chapter II Figures and Tables, pg. 71) for maximum number of counts vs the exposure time. The trends show a positive linear correlation between the exposure time and the peak neutron counts. The peak observed by nickel appears to be the strongest scatterer with the next strongest being iron, followed by germanium.

To determine detector resolution, a $2\theta$ sweep using an Inconel powder sample was performed. During this set of scans, two diffraction peaks swept across the detector. All
obtained images were integrated and peak positions within the field of view of the camera were determined by the channel number. The channel number peak positions are then plotted versus angular 2θ position as shown in figure 16 (Appendix: Chapter II Figures and Tables, pg. 72) and the slope yields the channel per degree value giving an idea of what the spatial resolution of the detector is for the given operating sample to detector distance. For the operating distance of 750mm, the Anger camera was found to have an approximate resolution of 57 pixels per degree.

Conclusions

Integration of the Anger camera in a diffraction instrument was successful. Development and implementation of shielding was part of the study and performed as intended (system performance without shielding was not investigated). For portable applications, a smaller footprint would be desirable however shielding dimensions are geometrically determined by sample to detector distance. Overall, the Anger camera proved to be a viable instrument for neutron diffraction measurements. The results show a high degree of 2-D spatial resolution and for the working distance of 750 mm the Anger camera was found to cover a 2θ range of approximately 8°. Future work will be aimed at evaluating the possibility of using the Anger camera for residual strain measurements; it will be critical to determine the magnitude of the strain change that can be determined by processing the two-dimensional images recorded by the Anger camera and successfully resolving shifts in peak position.
References

Chapter III. Application of high-sensitivity Anger camera to laboratory-based neutron generators for potential diffraction applications

This chapter is a slightly revised version of a paper with the same title currently under review for submission in 2022 to a targeted journal by Matthew W. Seals, Stephen B. Puplampu, Dayakar Penumadu, Richard A. Riedel, Stuart Miller, and Joshua McCumber.
Abstract

Neutron diffraction experimentation is a widely used form of non-destructive mechanical testing. Facilities which provide instrumentation to carry out such tests are built around high-flux sources. Such sources include reactor and spallation-based sources such as those found at the High Flux Isotope Reactor (HFIR) and at the Spallation Neutron Source (SNS) withing Oak Ridge National Laboratory (ORNL). There exists a wide degree of interest into the development of a neutron a diffraction instrument leveraging a lab-based neutron generator. Such an instrument would facilitate diffraction experimentation independent of a reactor or spallation source. To address the greatly reduced flux such an instrument would exhibit, use of a neutron diffraction optimized high-sensitivity Anger camera will be employed. Leveraging recent developments in the respective fields of diffraction optimized neutron detection, and DT (Deuterium-Tritium) gas high-yield neutron generators, the feasibility of the development of a lab-based diffraction instrument was evaluated. A rocking curve was obtained using a crude pyrolytic graphite monochromator.

Introduction

Neutron diffraction experimentation is a non-destructive means of mechanical testing of engineering materials by analysis of shifts in the Bragg angle,$\theta$, of scattered neutrons from a sample[1].

$$\lambda = 2dsin\theta$$ (6)
Target applications seek to find $hkl$ lattice strains incurred by a material through mechanical loading and heating/cooling cycles\cite{2, 3}. The shift in scatter angle from a stressed vs. unstressed components reveals the existence and severity of these residual mechanical effects. Such residual stress and strain to a material signals potential failure points of a material allowing for prediction of mechanical failure of a part before it occurs\cite{2}.

Diffraction experiments are typically carried out at facilities based on reactor and spallation neutron sources such as the High Flux Isotope Reactor (HFIR)\cite{4}, and the Spallation Neutron Source (SNS)\cite{5} respectively. HFIR, and SNS only represent two such facilities of many located world-wide. Visiting one of these facilities to carry out an experiment entails a great expenditure of time and financial costs including travel to the appropriate beam-line facility. Due to the demand for time on these various instruments time slots are allocated to researchers, typically on the order of several days, in which the researcher can set up their experiment and collect data. For these reasons access to neutron diffraction experimentation is quite limited in its availability and application.

Traditionally, lab-based neutron generators did not provide the flux necessary to facilitate their use with neutron diffraction instruments providing $10^7 \sim 10^8$ neutrons per second. However, given recent developments by the Phoenix Nuclear technology company with high yield DT(Deuterium-Tritium) gas neutron generators, sources can generate up to $10^{13}$ neutrons per second\cite{6}. Compared to the typical yield of nuclear reactors generating $10^{14} \sim 10^{17}$ neutrons per second\cite{7}. This source, although not as capable as a reactor, takes up a footprint of $\sim 32.3$ square feet (room size). In addition to a high yield lab-based neutron generator, a highly sensitive neutron detector technology is to be leveraged for improved signal
to noise for diffraction signal capture. Recent concern for shortages in He-3 has sparked a great deal of interest into He-3 independent detector technologies[8]. Such a detector has come from research efforts by the detectors group at ORNL. This imaging device is based on Anger logic architecture and is known colloquially as “Anger camera”[9]. Anger camera has seen great success at the SNS in recent years with comparable neutron sensitivity to that of He-3[10-12]. The latest generation of Anger camera provides a wide area of detection <detection area> with a resolution of 0.5mm ~ 1mm. The monolithic camera takes on a form factor of <length, width, height> weighing less than ten pounds, ideal for easy positioning in compact spaces. Image data is transferred over a TCP connection to a client PC located remotely to the detector facilitating easy remote operation. Given the advancement into neutron generation and detection these two technologies represent, it is conceivable the roles they can play into the development of a lab-based neutron diffraction instrument. Given the compact nature of the source in comparison to reactor and spallation sources, these instruments could provide fast and safe installation at facilities with a need to perform quick and easy diffraction experimentation.

**Materials and methods**

A lab-based neutron generator, depicted in figure 17 (Appendix: Chapter III Figures and Tables, pg. 73) was employed as a neutron source capable of producing on the order of $10^{13}$ neutrons per second. This source was located within a neutron shielded bunker of approximately 12ft wide by 30ft long on the interior. The source transmits neutrons through a port hole of 3” in diameter. Multiple adjustable height tables were set-up at center height with the neutron porthole. The tables provide a stable uniform plane of known height which instruments can be placed. The imaging device utilized was a monolithic neutron-sensitive
Anger camera provided by Oak Ridge National Laboratories detector group. This camera provides a 105mm x 105mm field of view with a resolution of 0.5mm ~ 1.0mm. A panel of single crystal pyrolytic graphite was constructed and attached to a remotely controlled rotating stage system depicted in figure 18 (Appendix: Chapter III Figures and Tables, pg. 74). The pyrolytic graphite panel acts as a crude single crystal monochromator[13] with the rotational axis acting as a wavelength selection method.

Transmission mode images were taken with the Anger camera using borated aluminum masks with 1mm holes spaced 1cm apart, and with slots of increasing width from 0.5mm to 4mm depicted in figure 19 (Appendix: Chapter III Figures and Tables, pg. 75). Borated polycarbonate sheeting was used to reduce over exposure which would result in damage to the camera. The port hole is surrounded in a frame of lead bricks to help reduce influence of unwanted gamma generated by the DT gas source. Open beam images were taken along with images using the 1mm hole mask as well as the slotted mask for an exposure time of 300 seconds for each.

The pyrolytic graphite panel was placed in front of the port hole and positioned at an angle by which a wavelength of 2.4Å could be selected which is satisfied with \(2\theta = 44^\circ\). The Anger camera was placed in line with the pyrolytic graphite panel such that the resultant monochromatic neutrons can be detected and compared to background counts as shown in figure 20 (Appendix: Chapter III Figures and Tables, pg. 76). To quantify the presence monochromatic neutrons can be quantified by counts compared to background. These counts in relation to the angle of the monochromator can be plotted as a rocking curve. The pyrolytic graphite panel was rotated from \(2\theta = 28^\circ\) to \(2\theta = 62^\circ\) in increments of 2° with the number of
counts recorded at each increment for 60 seconds. Results from this test were plotted as the number of counts vs the angle of the monochromator.

**Results and discussion**

Transmission mode images were taken for open beam and dark field as well as for both borated aluminum masks figure 19 (*Appendix: Chapter III Figures and Tables, pg. 75*). As a result of previous exposure of the Anger camera in transmission mode without a moderator material the Silicon Photomultipliers (SiPMs) were damaged resulting in reduced resolution and bright spots in the image that are not resultant from neutrons.

Figure 21-A (*Appendix: Chapter III Figures and Tables, pg. 77*) illustrates an open-beam image where the detector was exposed to the beam covered by a plate of borated polycarbonate covering the face of the Anger camera. Figure 21-B (*Appendix: Chapter III Figures and Tables, pg. 77*) illustrates a dark-filed image taken by the Anger camera with the source shut off. The bright spots on the image are because of earlier damage to the SiPMs due to over exposure. Figure 21-C (*Appendix: Chapter III Figures and Tables, pg. 77*) illustrates the image obtained by exposure through the borated mask featuring 1mm holes spaced 1cm apart. Figure 21-D (*Appendix: Chapter III Figures and Tables, pg. 77*) illustrates the image obtained by exposure through the borated mask featuring the 0.5mm to 4mm slits. In this figure the slits can be used to gauge what the limits are for resolving features in transmission mode. The camera struggles to resolve the 0.5mm slits.

The Rocking curve test was performed as depicted in figure 22 (*Appendix: Chapter III Figures and Tables, pg. 78*). collecting 18 samples with the pyrolytic graphite panel from $2\theta = 28^\circ$ to $2\theta = 62^\circ$ with the angle of interest being $2\theta = 44^\circ$. At increments of $2^\circ$ neutrons were
counted for 120 seconds and the total number of counts in that period recorded. It was
determined from existing data that it would be expected to see neutrons diffracted from the
pyrolytic graphite when it satisfies the angle $2\theta = 44^\circ$. The red box outlining the $2\theta$ range of
$42^\circ \sim 48^\circ$ displays a peak in intensity falling steadily down to the upper limit of the angular
range.

**Conclusions**

The transmission images taken using the resolution mask demonstrated the capability of
some imaging capability Anger camera could offer for these sources; however, the resolution is
much worse than what would be found with a typical flat panel detector. For imaging capability
typical CCD flat panel detectors should be leveraged. However, for diffraction imaging, Anger
camera proved capable of resolving a rocking curve from neutrons scattered from a single
crystal pyrolytic graphite panel. The rocking curve obtained and illustrated in figure 22
(Appendix: Chapter III Figures and Tables, pg. 78) clearly demonstrates the presence of
neutrons above background levels.

For better results in future experimentation, it is necessary to employ the use of a more
efficient bent silicon monochromator to improve the flux of the monochromatic beam. The
pyrolytic graphite panel is a crude monochromator at best. A secondary method of performing
diffraction that would completely negate the use of a monochromator would be a time-of-flight
method. Given the source could be pulsed, diffraction experimentation could be performed
using neutron time-of-flight. Future optimization of a DT gas source for diffraction application
could be demonstrated by exploring methods in which the source could be rapidly pulsed on
and off multiple times per second.
Further, care should be taken as to ensure the Anger camera is not overexposed directly to the beam which resulted in damage to the SiPMs for this experiment. An alternative method would be to leverage Multi-Anode Photomultiplier tubes which will not incur damage under overexposure. A redesign of the camera may be required for this optimization; however, such a camera would demonstrate itself to be ideal for this application.
References


8. *Helium-3 Shortage: Supply, Demand, and Options for Congress (R41419)*.


Chapter IV. Development of Weighted-Sum-based Compact Anger camera

This chapter is a slightly revised version of a paper with the same title currently under review for submission to a targeted journal in 2022 by Matthew W. Seals, Richard A. Riedel, Dayakar Penumadu, and Milton N Ericson.
Abstract

Traditional Anger camera utilizing resistor network based discretized positioning circuits (DPCs) are in wide use for spatially resolved radiation detection. A resolution of 6mm ~ 4mm can be expected with these devices when coupled to a Hamamatsu H8500 multi-anode Photomultiplier Tube (MAPMT). Anger camera has gained attention in the neutron diffraction community as a replacement of Helium-3 based detectors due to recent shortages of helium-3. However, resistor-based designs are difficult to optimized for diffraction applications. Recent developments from the Oak Ridge National Lab (ORNL) detector group have yielded a high-resolution neutron diffraction optimized Anger camera design capable of electronically filtering out gammas. This design can yield a 1mm resolution, compared to resistor-based designs at 6mm ~ 3mm typical. Performing gamma discrimination with the resistor-based design is difficult due to the need for direct coupling of high impedance outputs to the resistor-network. A weighted-sum-based Anger camera design provides a low-cost, lower-resolution alternative to higher resolution Anger camera architectures while providing similar gamma discrimination capability.

Introduction

Recent shortages in the supply chain of helium-3 have spurred research into development of neutron diffraction optimized Anger camera technologies.[1] Detector research at Oak Ridge National Lab (ORNL) has yielded a neutron diffraction optimized Anger camera capable of achieving approximately 1mm resolution[2, 3]. At spallation and reactor-based diffraction beam lines[4-6] there exists a high background of gamma which effects the Signal to
Noise Ratio (SNR) of the neutron diffraction signal. This optimized Anger camera overcomes the gamma background by employing a filtering method based on electronic pulse shape discrimination[7-9]. Classic resistor network-based Anger camera designs do not allow for accurate pulse shape discrimination as they do not address anode gain non-uniformity prevalent in all manufactured Multi-Anode Photomultiplier Tubes (MAPMTs)[10, 11]. Due to this shortcoming, the resistor network architecture-based Anger camera is not highly viable for diffraction instruments requiring research into methods better optimized for diffraction imaging. A weighted-sum-based approach to Anger camera provides a diffraction-optimized replacement to the traditional architecture with comparable resolution at a lower cost and complexity than that of the high-resolution design.

The way in which anode gain non-uniformity is addressed by high-resolution Anger camera is by applying a transimpedance amplifiers to each channel[2, 12]. The feedback resistor for each transimpedance amplifier is sized to apply a gain to each channel such that all channels exhibit the same photo gain. The classic Anger resistor network requires high impedance inputs, such as a direct input from a photomultiplier tube. The output from the preamplifier array required to correct anode gain non-uniformity is low impedance due to the low output resistance from the transimpedance amplifiers[13]. These low impedance outputs make the preamplifier array incompatible with the resistor network. Any current introduced into the network from an amplifier will be sunk back into the output of neighboring amplifiers. The High-resolution camera finds the point of incidence of a neutron by summing the rows and columns of the MAPMT. For n *n*-by-*n* MAPMT, *n* column sums and *n* row sums are obtained providing two numerical sets. Gaussian fitting is applied to these sets to obtain the gaussian
mean, $\mu$, for the rows and columns, $\mu_{\text{rows}}$ and $\mu_{\text{columns}}$ respectively. The point of incidence can be estimated to be at the cartesian position ($\mu_{\text{columns}}, \mu_{\text{rows}}$), or $(X, Y)$. The weighted-sum-based architecture finds the point of incidence of a neutron in a partially similar manner.

The rows and columns of the MAPMT are summed; however, two weighted-sums are applied to the rows and two weighted-sums are applied to the columns. The resultant signals from the four weighted-sums can be used to numerically calculate the position of incidence of a neutron. The advantage of the weighted-sum-based method over the high-resolution Anger camera is the reduced hardware overhead and cost. The high-resolution camera reduces an $n$-$by$-$n$ MAPMT with $N$ outputs to $2\sqrt{N}$ to channels to condition and sample. The weighted-sum Anger camera architecture reduces $N$ outputs to a constant four. For this reason, the required hardware needed determine the point of incidence will always be less than that of the high-resolution camera. The primary advantage of the weighted-sum architecture over the traditional resistor network architecture is the ability to provide anode gain non-uniformity correction; and hence, pulse shape discrimination. Weighted-sum-based Anger camera offers a low-cost, low-resolution architecture optimized for applications in neutron diffraction imaging.

**Theory and modeling**

The system can be broken down into three primary stages: preamplification, weighted-sum application, and sampling. Preamplification provides transimpedance conversion of currents from the MAPMT as well as correction of anode gain non-uniformity by sizing the feed-back resistor of each amplifier. The sized feed-back resistor sets the gain to normalize each anode about the anode with the highest photo-gain. For an 8-by-8 MAPMT each of the 64
outputs are fed into a transimpedance amplifier individually producing 64 individual outputs.

The gain-corrected signals from the preamplifiers are then positionally encoded into four positional signals by the weighted-summing stage. The weighted-summing stage sums the eight rows and eight columns into two numerical sets denoted $R$ and $C$ respectively, where each component can be denoted $r_i, i \in [1,8]$ and $c_i, i \in [1,8]$. Two weighted-sums are applied to each numerical set which can be generalized as $\Sigma_1$, and $\Sigma_2$ by the following two expressions:

$$\Sigma_1 = \frac{1}{8}a_1 + \frac{1}{7}a_2 + \frac{1}{6}a_3 + \frac{1}{5}a_4 + \frac{1}{4}a_5 + \frac{1}{3}a_6 + \frac{1}{2}a_7 + a_8$$

$$\Sigma_2 = \frac{1}{8}a_8 + \frac{1}{7}a_7 + \frac{1}{6}a_6 + \frac{1}{5}a_5 + \frac{1}{4}a_4 + \frac{1}{3}a_3 + \frac{1}{2}a_2 + a_1$$

Where, $a$, can be generalized as a numerical set with eight members denoted, $a_i, i \in [1,8]$.

Applying equations 5.1 and 5.2 to the row and column sums, $R$ and $C$ yields the following four expressions:

$$Y_1 = \frac{1}{8}r_1 + \frac{1}{7}r_2 + \frac{1}{6}r_3 + \frac{1}{5}r_4 + \frac{1}{4}r_5 + \frac{1}{3}r_6 + \frac{1}{2}r_7 + r_8$$

$$Y_2 = \frac{1}{8}r_8 + \frac{1}{7}r_7 + \frac{1}{6}r_6 + \frac{1}{5}r_5 + \frac{1}{4}r_4 + \frac{1}{3}r_3 + \frac{1}{2}r_2 + r_1$$

$$X_1 = \frac{1}{8}c_1 + \frac{1}{7}c_2 + \frac{1}{6}c_3 + \frac{1}{5}c_4 + \frac{1}{4}c_5 + \frac{1}{3}c_6 + \frac{1}{2}c_7 + c_8$$

$$X_2 = \frac{1}{8}c_8 + \frac{1}{7}c_7 + \frac{1}{6}c_6 + \frac{1}{5}c_5 + \frac{1}{4}c_4 + \frac{1}{3}c_3 + \frac{1}{2}c_2 + c_1$$

Four resultant signals generated from the weighted-summing operation $X_1, X_2, Y_1$ and $Y_2$ are used to find a cartesian mapping, $(X, Y)$, to the point of incidence of the photon on the MAPMT by the following two expressions:
\[
X = \frac{X_2 - X_1}{X_2 + X_1} \quad (3.1)
\]
\[
Y = \frac{Y_2 - Y_1}{Y_2 + Y_1} \quad (3.2)
\]

The positional calculation is trivial enough from an analytical sense; however, for applications purposes it must be kept in mind that the four outputs \(X_1, X_2, Y_1\) and \(Y_2\) will be fast signals decaying around 50ns \(\sim\) 100ns. The capture of the positional signals from the weighted-summing stage requires some peak holding technique for conventional analog-to-digital (A/D) sampling techniques. For nuclear instrumentation it is not uncommon to use a gated integrator to apply an electronically implemented integration function to fast pulses to capture and hold signal information before sampling the signal. Conceptualization of the weighted-summing method is illustrated by figure 23 (Appendix: Chapter IV Figures and Tables, pg. 79).

A gated integrator, in its simplest form, can be conceptualized as a switched RC circuit. With a resistor of resistance, \(R\), and a capacitor of capacitance, \(C\). The transfer function of this circuit can be expressed as:

\[
V_{out} = \frac{1}{RC} \int V(t) dt \quad (4)
\]

The depiction of a gated integrator in figure 24 (Appendix: Chapter IV Figures and Tables, pg. 79) illustrates this concept. \(V(t)\) is the input waveform to the integrator, and \(V_{out}\) is the integral of the \(V(t)\) waveform up to time, \(t\). Each output from the weighted-summing circuit can be sampled by applying a gated integrator to each signal which integrates on an incoming signal and holds the integral of that signal until it can be sampled using a conventional analog to digital converter. The sampled integral can apply to equations 7.1 and 7.2 to calculate the...
cartesian point of incidence of the photon on the MAPMT with respect to the channel being integrated.

Simulations in LtSpice were carried out to demonstrate the effectiveness of a theoretical system architecture as described by the weighted-summing method in conjunction with gated integrators as a sampling mechanism. The simulation was driven by a python program which would run the spice netlist as a batch file using system calls. The simulation has 64 inputs, one for each channel of an 8x8 MAPMT. By modifying the netlist, a current pulse can be directed into any one of these inputs independently. Each current input is directed through a preamplifier, then to a simulation weighted-summing circuit. The four resultant outputs are logged as spice raw files to be post processed by the python program. A numerical integration on \( t = 0 \) to \( t = 200\text{ns} \) is then applied to the four output waveforms resulting in the four values \( X_1, X_2, Y_1 \) and \( Y_2 \). These values were used to calculate the cartesian position from eq. 7.1 and 7.2. Outputs and calculations for a single point are shown in figure 26 (Appendix: Chapter IV Figures and Tables, pg. 81).

Results from the simulation provide evidence to the efficacy of the concept for determining the position of incidence of a photon on an 8x8 MAPMT. Each input to the simulated weighted-summing circuit, followed by integration of the four outputs, results in calculation of a point that maps each of the inputs to its own distinct cartesian mapping. The mapping is visualized via plotting the \( X, Y \) pairs onto a simple scatter plot annotated to the input excited to result in that point. The simulation results in a full cartesian mapping of 64 inputs to outputs illustrated by figure 25 (Appendix: Chapter IV Figures and Tables, pg. 80).
Architecture
Realization of an Anger camera based on the weighted-sum method into hardware was done by construction of four sub-assemblies. The first sub assembly, four preamplifier cards, interfaces directly to the 8x8 MAPMT shown by figure 27-1 (Appendix: Chapter IV Figures and Tables, pg. 82). The preamplifiers provide each channel of the MAPMT with a transimpedance amplifier capable of performing a transimpedance conversion and anode gain matching[12]. The weighted-summing operation is performed by the summing board depicted in figure 27-2 (Appendix: Chapter IV Figures and Tables, pg. 82). The summing board accepts the four preamplifier cards, summing the channels in row and column format and then applying the weighted-sums. The four outputs from the summing board( $X_1, X_2, Y_1, Y_2$ ) contain the positional information on the point of photon incidence. The four positional signals are held and sampled by the integrator board illustrated in figure 27-3 (Appendix: Chapter IV Figures and Tables, pg. 82). The integrator board mates to the summing board providing four integration and sampling channels triggered to function on the presence of a signal from the summing board. The final board in the stack provides power management and a bridge between the rest of the system and a MicroZed Zynq-7000 SOC development board depicted by figure 27-4 (Appendix: Chapter IV Figures and Tables, pg. 81). The MicroZed board utilizes the Zynq-7000 SOC as a digital signal processor and an interface to a client PC shown by figure 27-5 (Appendix: Chapter IV Figures and Tables, pg. 82). The two components not custom designed and fabricated are the Hamamatsu H8500 MAPMT (figure 27-6) (Appendix: Chapter IV Figures and Tables, pg. 82), and the MicroZed development board (figure 27-5) (Appendix: Chapter IV Figures and Tables, pg. 82).
A single preamplifier card is comprised of 16 transimpedance amplifiers (four cards makes 64 channels). Each preamplifier has a sized feed-back resistor normalizing the MAPMT output to correct for anode gain non-uniformity. The cards are configured to plug directly into the back of an H8500 8x8 MAPMT with the outputs plugging directly into card-edge connectors on the back side of the summing board.

The uncorrected and corrected gain maps taken from the H8500 by itself and with the preamplifier cards is illustrated by figure 28 (Appendix: Chapter IV Figures and Tables, pg. 83). The uncorrected map demonstrates a maximum gain difference of 38%, the corrected map demonstrates an improved gain difference of 10%.

The summing board accepts the four preamplifier cards with the 64 channels from the cards being treated as pass-through channels for each channel of the MAPMT. The summing board uses opamps in summing fashion with two-factor gain to sum the rows and columns into eight row and column sum signals\cite{13}. The summed row and columns are then fed into opamps capable of providing the weighted-summing operation. The four weighted-summing amplifiers take eight inputs each with input and feedback resistors sized proportionally to provide transfer functions as eq. 5.1 and 5.2. The two amplifiers providing functions for eq 5.1 to produce $X_1$, and $Y_1$ from the row and column sums exhibiting transfer functions as demonstrated by eq. 6.1 and 6.3. Two further amplifiers provide functions for eq. 5.2 to produce $X_2$, and $Y_2$ from the row and column sums exhibiting transfer functions as demonstrated by eq. 6.2 and 6.4. The four positional signals from the summing board, $X_1, Y_1, X_2$, and $Y_2$ as well as the row sums are passed onward to the integrator board.
The integrator board provides four channels with signal chains comprised of a 2ns delay line, a gated integrator[14], and a 3MS/s ADC. The eight row sums from the summing board are fed to a summing amplifier of unity gain to produce an analog signal of relative magnitude comparable to the amount of total current from the MAPMT[13]. This sum is termed the “photosum” and is used to trigger a comparator with its non-inverting input referenced to an adjustable voltage source. Adjustment of the voltage source referenced by the non-inverting input of the comparator sets a pulse height threshold the photosum must exceed to trigger the comparator[8]. The 3.3V trigger pulse from the comparator signals the Digital Signal Processor that signals of interest are to be expected through the 200ns delay line to the gated integrator. The conceptualized illustration of the integrator board for a single channel is depicted by figure 29 (Appendix: Chapter IV Figures and Tables, pg. 84).

The integrator consists of an opamp, an analog 2:1 switch, a resistor, and capacitor. The switch, when unasserted, will direct the feed-back path of the opamp through a resistor to create a simple unity-gain situation. When asserted, the switch directs the feed-back path through a capacitor creating an integrator. The switch for each channel is triggered by TTL signals from the digital signal processor. The functionality of the gated integrator in both unity mode and integration mode is depicted by figure 30 (Appendix: Chapter IV Figures and Tables, pg. 84). The DSP directs timing signaling to the integrators and digital conversion of their outputs[15]. When a signal from the comparator asserts the presence of incoming data the DSP will “know” there is approximately 200ns across the delay line before the signal shows up across the integrator. This 200ns approximation is used to synchronize the triggering of the gated integrator with the arrival of the signal. Figure 31 (Appendix: Chapter IV Figures and
Tables, pg. 85) provides a pseudo timing diagram to illustrate the order of events and timing in the sampling procedure.

The digital signal processor (DSP) comprised of a MicroZed development board, interfaces with the integrator through an interface board. The interface board provides breakout and mating for the DSP as well as power control and regulation to the system. The DSP hosts a Xilinx Zynq-7000 System On Chip (SOC) featuring a dual core, 32-bit arm cortex A9 processing system memory mapped to an artix-7 FPGA. The FPGA featured in the SOC is responsible for interfacing with the system to capture data and set voltage offsets as needed. The integrator features four ADCs (one for each gated integrator output) and nine DACs (digital to analog converters) to set reference voltages and offsets. When the DSP is triggered by the integrator board by previously discussed mechanisms, the DSP will begin the sampling process. A high-level illustration of this system and the associated signals between the DSP and the integrator board is depicted by figure 32 (Appendix: Chapter IV Figures and Tables, pg. 86)

The sampling process involves gauging the pulse width of the signal from the comparator, given the width is sufficient to be of interest the gated integrators will be set to integrate[9]. The DSP will then wait for 300ns to allow for the signal to arrive from the delay line and integrate for 100ns. After 300ns the ADCs will be asserted to sample the output of the gated integrator and perform the analog to digital conversion. The digital information is then stored in RAM on board the FPGA to be used to calculate the point of incidence of the photon that triggered the capture sequence. The processing systems on board the SOC hosts a TCP server that interfaces with a client PC. A PC will connect to this host where it will pull data captured by the FPGA and calculate the point of incidence. When a request is made by the
client, the processing system will transmit back image data to be interpreted by a python client running on board the connected PC.

**Design validation and testing methods**

To achieve a test to validate the design and test the ability to resolve light pulses between the anodes of the MAPMT a test bed was developed illustrated in figure 33 (Appendix: Chapter IV Figures and Tables, pg. 86). This test bed uses a light-tight box (dark box) containing a two-axis stage, a pulsing light source, pass-throughs for cabling, and mounting plates for various break-out boards to do various tests. External to the dark box is a high-speed oscilloscope, power supplies, and a random waveform generator. The random waveform generator is used to drive the pulsed light source within the dark box to produce light pulses of desired duration and intensity. The oscilloscope offers four channels and a TCP connection with the capability of digitizing waveforms and transferring them over to a client PC.

This set-up was used extensively during system development for step-by-step validation as well as for final validation of the ability of the system to resolve light pulses between anodes in the MAPMT. Two benchmark tests were performed, the first involving the capability of the preamplifier cards and the summing circuit to encode the position of a photon into four positional signals. Second, being the test of the Anger camera as a monolithic system, to resolve the position of a photon on the MAPMT accurately and transmit the associated information back to a client PC.

The preamplifiers and the summing board encompass the sub-system of the camera responsible for encoding the position of a photon into a signal to be read-out of the device. The
performance of this sub-system will set the bar for how well the camera as a whole can operate. To ensure that the system will work as well as predicted in simulation and theory a break-out board was designed to accept the summing board. This break-out board provided four BNC connections to rout the positional signals to the external oscilloscope to be digitized and transferred to a PC. The MAPMT, preamplifier cards, summing board, and break-out board were assembled and mounted to the two-axis stage as depicted in figure 34 (Appendix: Chapter IV Figures and Tables, pg. 87). The stage was controlled externally by a stage controller and positioned the MAPMT under the pulsing light source to activate each anode individually. Each anode in the MAPMT was pulsed ten times, each pulse producing a response of four output waveforms \((X_1, X_2, Y_1, Y_2)\) read by the oscilloscope. These four signals were digitized and transferred to the PC for later post-processing. Post processing involved using a python program to process the four signals from each light flash into waveforms which could then be integrated over a 200ns time interval. The beginning of the integration interval is marked as the rising edge of each pulse as recorded by the oscilloscope. The resultant integrations for each of the four waveforms were then used to calculate the point of incidence of that corresponding light pulse. This was done for ten light pulses per anode of the 64 anodes in the 8x8 array.

The Anger camera was tested as system involving the whole assembly, not only to benchmark the system, but also to see what effects the sampling and digital signal processing hardware had on its performance relative to the performance of the weighted-sum positioning electronics by themselves. The system was mounted onto the two-axis stage below the fixed pulsed light source similarly to the set up previously described. In testing the camera, however, the only digital read-out electronics involved were those designed and implemented on the
camera. The camera was connected to a PC, via ethernet cable, outside the dark box. The MAPMT was positioned over the pulsed light source such that each anode received ten light pulses. The results calculated from the Anger camera were then transferred back to the PC as would happen under normal operation. After benchmarking the capability of the camera to resolve light pulses between anodes, it was then exposed to a Cf-252 neutron source to gain a flood image of 10,000 neutron counts. The points of incidence of neutrons from the camera were then binned to an 8x8 pixel map via a python program running on board the host PC.

**Results and discussion**

The results from the dark box test yields a figure of merit to define how well the system could resolve the position of a light pulse between neighboring anodes. This gives a reasonable estimate of possible achievable resolution of the system. The ten light pulses over each anode can be assumed to be placed reasonable centered to the anode with not motion between pulses. Any variance in the position calculated for each pulse can then be assumed to be system error and results in reduction of possible resolution.

Both tests performed in the dark box involving placed photo-pulses yielded scatter plots of calculated positions for each photo-pulse. As each anode was exposed to ten photo-pulses, it would be expected under perfect performance that an 8x8 grid of points would be obtained where each point is ten perfectly overlapping points as the points are the result of light pulses flashed in the same location. Instead, what can be observed is ten light pulses clustering about a central point in an 8x8 grid. The reason for the variance in calculated location is due to stochastically and architecturally induced error which should be minimized as much as possible to improve resolution. The variance in scatter of the ten light pulses can be quantified as a
circle of minimum radius, \( r \), to encompass all ten points. The smaller this radius, the more accurately and consistently the system can resolve the position of a light pulse.

It can be observed in figure 35-A, B (Appendix: Chapter IV Figures and Tables, pg. 88) that the results from the summing board alone yielded results comparable to what would be expected from traditional resistor-based positioning circuits[11]. Such results as these proves the weighted-summing-based method to provide an acceptable replacement of resistor-network based designs. Although the weighted-summing method itself finds validation, the camera as a system did not yield the same results. For figure 35-C, D (Appendix: Chapter IV Figures and Tables, pg. 88), it can be observed that the addition of the integrator board and DSP as the read-out mechanism yielded a scatter plot which demonstrates consistent inaccuracy in its ability to calculate the position of the light pulse. The average scatter radius demonstrated by the summing board alone was 0.023 by table 1 (Appendix: Chapter IV Figures and Tables, pg. 89). the camera as a system yielded an average scatter radius of 0.12 by table 2 (Appendix: Chapter IV Figures and Tables, pg. 89). This represents an over five-times gain in error to the capability of the system.

Further illustrating the quality of the system to avoid overlap in spatially resolving photo-pulses between anodes of the MAPMT row and column plots can be demonstrated. The position of the photo-pulse is given by the weighted-summing operation as an ‘X’ and ‘Y’ component individually to a coordinate set. By plotting the X and Y components of each point against the column number and row number respectively, by visual inspection, it can be seen how distinctly photo-pulses are separated in X and Y.
Figure 36 (Appendix: Chapter IV Figures and Tables, pg. 90) illustrates the row and column plots for the data in figure 35 (Appendix: Chapter IV Figures and Tables, pg. 88) with regards to the weighted-summing board test (figure 35-A, B) (Appendix: Chapter IV Figures and Tables, pg. 88) and the Anger camera test (figure 35-C, D) (Appendix: Chapter IV Figures and Tables, pg. 88). The column plots are given by taking the X-component of the points calculated for the photo-pulse and plotting those components against the row they lie on. The row plots are given by taking the Y-component of the points calculated for the photo-pulse and plotting those components against the column they lie on. Given there were ten photo-pulses per anode, there are ten plots per column (against eight rows), and ten plots per row (against eight columns).

Overlap in the x-component value plots shows that the photo-pulse is not being properly resolved to the anode with regards to the column (in the 8x8 array) which the anode lies within. Overlap in the y-component value plots shows that the photo-pulse is not being properly resolved to the anode with regards the row which the anode lies within. No overlap shows there is an accurate and consistent mapping between the point of incidence of the photo-pulse and to its corresponding cartesian position. The Anger camera was exposed to a Cf-252 source for 10,000 counts and binned to an 8x8 grid producing the flat-field image in figure 37 (Appendix: Chapter IV Figures and Tables, pg. 91). The flat field shows a consistent distribution of counts about the MAPMT. This revels there is not bias in the positioning hardware to cause the counts to cluster about a specific region of the pixel mapping.
Conclusions

The weighted-summing method applied realized in hardware yielded results comparable to what would be expected from a resistor-based discretized positioning circuit. With the application of the integrator board and digital signal processor as the read-out mechanism the ability to resolve photo-pulses between anodes was greatly decreased. Some primary conclusions drawn from this data are the following:

1. The weighted-summing method works and can serve as a replacement to the resistor network based discretized positioning circuits in neutron diffraction optimized applications.

2. The Anger camera as a system proved to be incapable of resolving photo-pulses between anodes reliably. This decrease in performance with the introduction of the integrator board and DSP reveals that the read-out method requires further optimization.

3. Although the Anger camera could not resolve photo-pulses as intended the clustering of the photo-pulses between anodes can be seen to be in a rough 8x8 row/column pattern.

4. Further research and optimization of the read-out circuitry could prove to produce an Anger camera capable of 3mm ~ 6mm resolution making it on par with systems which utilize resistor network-based read-out methods.

The target goal of this work was to explore the use of a weighted-summing-based method of resolving the position of a neutron on a scintillator via an 8x8 MAPMT in a manner comparable to resistor-network-based designs. Ultimately, the weighted-summing method itself proved to be a comparable method in terms of resolution capability; however, the
Anger camera design based on this method will require further optimization. Research into the matter should entail a focus on optimization of the gated-integration method and sampling devices. Points of interest include possible sources of stochastic and induced noise within the electronics that would cause the output of the gated integrator to not reflect the output of the summing board. How might the integration effect the information contained within the positional signal from the summing board such the calculated position of the photo-pulse would be distorted.
References

1. Helium-3 Shortage: Supply, Demand, and Options for Congress (R41419).
Conclusions
Outlook for applications of Anger camera for lab-based diffraction applications

Anger camera has found wide use currently in applications for neutron diffraction experimentation. Looking to extending the state of the art of the technology and the applications of the technology could open new capabilities for neutron diffraction experimentation. Applying Anger camera to lab-based sources with comparably low fluxes to when compared with spallation and reactor-based sources proves to a promising path to the development of a lab-based neutron diffraction instrument. Further optimization can could be realized by augmenting an existing Anger camera to use MAPMTs or leveraging the newly developed weighted-summing Anger camera to prevent radiation damage. The pyrolytic graphite panel utilized for diffraction experimentation with the lab-based source is a poor monochromator. Utilizing a bent silicon monochromator could offer improved flux of the resultant monochromatic beam.

Implications and contributions of weighted-sum Anger camera research

A weighted-sum Anger camera acting as a neutron optimized analog to the original resistor based DPC fills a role currently unfilled within the state of the art of Anger camera. Currently all Anger camera technology optimized for neutron diffraction demonstrates high resolution (1mm ~ 0.5mm); however, this architecture is expensive to produce. When a wider field of view is more desirable than higher resolution it could be more cost effective to use He-3 based detectors. The weighted-sum-based Anger camera provides a cheaper alternative to high
resolution Anger camera with comparable resolution to traditional resistor network based DPC designs (3mm ~ 6mm). A large array of weighted-sum based Anger cameras for high FOV with a trade-off for poorer resolution would result in a system which would be a cost-effective alternative to He-3 detectors.

Weighted-sum-based DPC read-outs for Multi-Anode Photomultiplier Tubes (MAPMTs) are swappable with resistor network based DPCs. As both architectures produce four positional output signals, the only modification necessary is in the interpretation of the signals after sampling. With such a modification the user is provided with a system which corrects for anode gain nonuniformity and provides a basis for accurate pulse shape discrimination.

Inferences for further research

Development of lab-based diffraction instrument

Based on the experiments carried out in this work about the development of a lab-based neutron diffraction instrument, several aspects and modifications should be explored to. One largely contributing factor to poor signal to noise ratio for neutron diffraction is poor shielding against stray neutrons contributing to background noise. Working more closely with the manufacturer of the source to apply more appropriate shielding to suppress unwanted background gammas and neutrons. Techniques to reduce stray neutrons also includes the use of neutron waveguides to direct the polychromatic beam to a location away from the point of generation. This reduces the flux at the monochromator; however, it does a great deal to provide a lower background.
Improvement of the quality of the monochromatic beam can be gained by employing a task-specific monochromator. It is common for diffraction instruments utilizing a reactor source to employ bent-silicon monochromators. The bending the silicon reduces its mosaicity and thusly increases the $\frac{\Delta \lambda}{\lambda}$. The resultant beam, although composed of a broader spectrum of neutrons about the target wavelength, $\lambda$, has a much higher flux. This increase in flux will result in a much larger diffraction signal from the sample.

An alternative to monochromat ion would be explore options to pulse the beam to perform time-of-flight diffraction imaging. As the beam is electronically controlled, it is conceivable that a neutron source could be outfitted with the necessary modifications to leverage a pulsed beam for neutron diffraction.

A continual issue encountered with the lab-based source was the intensity of the background within the testing area being high enough to damage the Silicon PMTs used by the Anger camera. A modification to the Anger camera to accept more typical multi-anode photomultiplier tubes would eliminate this issue. A secondary approach to relieving background intensity lies in the shielding of the camera. A more robust shielding system applied to the camera itself would help to alleviate this issue as well.

**Weighted-sum-based Anger camera development**

The weighted-summing method provides excellent analog to the resistor network based DPC. Although the weighted-summing hardware proved capable, the read-out hardware demonstrated a need for further optimization. Reduction in resolution and the inability of the camera to resolve photo pulses between anodes could result from several factors. Some of
these factors will include electrical noise, poor offsets, improper biasing and possibly factors involved in the design of the integrators themselves. These factors should be explored in more detail both from simulation and empirically from the test-bench. Possible improvements to the hardware design could be made to improve upon these effects for better resolution.

With an improvement on the read-out method to obtain satisfactory resolution, read-out hardware should be developed to accommodate an array of MAPMTs. By increasing the number of accommodated MAPMTs the field of view of the camera could be increased accordingly. The real potential of a weighted-sum-based camera is the ability to scale the camera FOV with further MAPMTs at reduced cost when compared to high resolution neutron diffraction optimized Anger camera.
Appendix
Figure 1: Illustration of a neutron diffraction experiment with a diffraction pattern (lower left).
Figure 2: Illustration of the deformation of the atomic lattice causes a shift in the diffraction angle for a 4A neutron.
Figure 3: Anger camera setup at CG1A beam line to see a diffraction peak from a germanium powder sample.
Figure 4: Helium-3 tube based neutron detector illustrated with a cross section of the internal of the helium-3 tube, and the nuclear interaction resultant from a neutron with helium-3.

Figure 5: Illustrated method by which helium-3 tubes are used to spatially resolve a neutron.
Figure 6: Illustration of internal mechanisms of a single photomultiplier tube with a neutron sensitive scintillator.
Figure 7: Illustration of a resistor-based Discretized Positioning Circuit (DPC).

Figure 8: Illustration of an Anger camera from a 64-channel PMT multiplexing charge from the 64 channel PMT (MAPMT) deriving the position as an X,Y coordinate pair.
Figure 9: Image of the latest generation Anger camera produced by ORNL detectors group.
Figure 10: Figure of the shielding and alterations made to the HB2B diffraction instrument
Figure 11: Depicted left: a diffraction pattern imaged using large area neutron sensitive Anger camera. Pictured left is the vertical integration of the image to the right. The image size is 512 x 512. The X-axis of the vertical integration is the image column, and the Y-axis is the counts.

Figure 12: Pictured left, is an image of two diffraction peaks from an Inconel sample with a peak-fitting performed to its vertical integration pictured to its right.
Figure 13: Finding the FWHM programmatically simply involves taking the peak of the curve, dividing it by two, and taking the two points at which the curve crosses this position. Taking these two points, the width is found simply as taking the difference between them.

\[ W = x_2 - x_1 \]

\[ H[x_{\text{max}}] = 1.0 \]
\[ H[x_{\text{max}}]/2 = 0.5 \]
\[ x_1 = 36.1 \]
\[ x_2 = 63.8 \]
\[ W = x_2 - x_1 = 27.7 \]
Figure 14: Above the conditioned peaks gathered for Iron, Germanium, and Nickle for 1200 seconds exposure time are depicted.
Figure 15: Raw peak maximum counts vs the exposure time of the camera for Iron (Fe), Germanium (Ge), and Nickel (Ni) with linear regressions performed for each of the three sets.
Figure 16: Top: camera swept across a diffraction pattern from Inconel (311) from 91.5 to 96.5 degrees showing the motion of the diffraction pattern across the face of the camera. Bottom: a plot of the change in peak position as a function of the
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Figure 17: Anger camera experimental setup in transmission mode facing the source porthole with borated polycarbonate sheets acting as a moderator material.
Figure 18: Panel of pyrolytic graphite affixed to a stepper motor acting as a rotation stage to be driven remotely for wavelength selection. The panel is sitting directly in front of the source port hole.
Figure 19: Borated aluminum masks with 1mm holes spaced 1cm apart (A), and 4mm to 0.5mm slits (B). The list progression for ((B) is 0.5mm, 1mm, 2mm, 3mm, 4mm.
Figure 20 (A) Illustrates the set up with the Anger camera to see scattered neutrons from the pyrolytic graphite panel. (B) is an image taken of the Anger camera and pyrolytic graphite panel in position to the port hole of the source.
Figure 21: (A) open beam and poly cover for 5600 seconds exposure and 2110170 counts. (B) Dark filed source turned off exposed for 5600 seconds and 26639 counts. (C) exposed to beam with 1mm hole mask for 600 seconds and 844148 counts. (D) exposed to beam with slits mask for 600 seconds and 1541544 counts.
Figure 22: Rocking curve for pyrolytic graphite single crystal rotated from $2\theta = 28^\circ$ to $2\theta = 62^\circ$ in $2^\circ$ increments. The Anger camera was placed at approximately $2\theta = 44^\circ$. 
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Figure 23: Illustration of procedure for row and column summing of 8x8 MAPMT with applied weighted-sums to row and column sum sets producing the four positional outputs.

Row and column summing operations

Figure 24: Illustration of gated integrator integrating a pulse of 100ns in duration.
Figure 25: Cartesian positions calculated for the 64 inputs of the simulation. Input number annotated beside each point.
**Analytical integration for outputs**

\[
\begin{align*}
&\int_{t=0}^{t=200e^{-9}} Y_1 \, dt = R_1 = 9.99e - 8 \\
&\int_{t=0}^{t=200e^{-9}} Y_2 \, dt = R_2 = 1.33e - 8 \\
&\int_{t=0}^{t=200e^{-9}} X_1 \, dt = C_1 = 9.99e - 8 \\
&\int_{t=0}^{t=200e^{-9}} X_2 \, dt = C_2 = 1.33e - 8
\end{align*}
\]

\[
X = \frac{C_1 - C_2}{(C_1 + C_2)} = -0.764 \quad Y = \frac{R_1 - R_2}{(R_1 + R_2)} = -0.764
\]

---

Figure 26: Simulation response for current pulse on channel 1 and corresponding calculations to a cartesian position.
Figure 27: Overview of camera assembly. 1) preamplifier cards, 2) weighted-summing board, 3) integrator board, 4) DSP interface (power management), 5) DSP.
Figure 28: Relative gain map of H8500 MAPMT uncorrected (left) and corrected (right).
Figure 29: Signal chain for one of the four channels of the integrator circuit. The gated integrator illustrated here is a conceptualization of the integrator as a switched RC circuit.

Figure 30: Illustration of the gated integrator as an opamp with a switch in the feedback path between a resistor and a capacitor. The resistor in the feedback path sets the amplifier to unity-gain mode. The capacitor in the feedback path sets the amplifier into integration mode.
Figure 31: Pseudo timing diagram of the capturing sequence. The DSP is triggered, then the gated integrator is asserted for 300ns (200ns delay + 100ns signal). The output of the integrator is then sampled.
Figure 32: Illustration of the Digital signal processor and all associated interfaces to the integrator board

Figure 33: Illustration of testing apparatus for both the camera and for the weighted-summing electronics by themselves.
Figure 34: Image of the testing fixture for the summing board as a stand-anode photon-positioning device. 1) pulsed light source (controlled externally). 2) H8500 MAPMT. 3) four preamplifier cards. 4) summing board. 5) break-out board.
Figure 35: A) Scatter of ten points for each anode using weighted-summing electronics only. B) scatter of ten points for each anode using only weighted-summing electronics with minimum radius circle drawn around each cluster. C) scatter of ten points for each anode using Anger camera system. D) scatter of ten points for each anode using Anger camera system with minimum radius circle drawn around each cluster.
Table 1: Anode row/column organized radius diameter for weighted-sum electronics test.

<table>
<thead>
<tr>
<th>Weighted summing circuit cluster radii</th>
<th>column 1</th>
<th>column 2</th>
<th>column 3</th>
<th>column 4</th>
<th>column 5</th>
<th>column 6</th>
<th>column 7</th>
<th>column 8</th>
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<td>0.029</td>
<td>0.013</td>
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<td>0.026</td>
<td>0.03</td>
<td>0.026</td>
<td>0.027</td>
</tr>
<tr>
<td>row 3</td>
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<td>0.015</td>
<td>0.043</td>
<td>0.034</td>
<td>0.044</td>
<td>0.023</td>
<td>0.021</td>
<td>0.02</td>
</tr>
<tr>
<td>row 4</td>
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<td>0.029</td>
<td>0.04</td>
<td>0.016</td>
<td>0.023</td>
<td>0.025</td>
<td>0.026</td>
<td>0.017</td>
</tr>
<tr>
<td>row 5</td>
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<td>0.016</td>
<td>0.026</td>
<td>0.025</td>
<td>0.018</td>
<td>0.03</td>
<td>0.016</td>
<td>0.02</td>
</tr>
<tr>
<td>row 6</td>
<td>0.015</td>
<td>0.015</td>
<td>0.026</td>
<td>0.028</td>
<td>0.029</td>
<td>0.021</td>
<td>0.022</td>
<td>0.029</td>
</tr>
<tr>
<td>row 7</td>
<td>0.022</td>
<td>0.013</td>
<td>0.022</td>
<td>0.031</td>
<td>0.023</td>
<td>0.019</td>
<td>0.023</td>
<td>0.026</td>
</tr>
<tr>
<td>row 8</td>
<td>0.014</td>
<td>0.013</td>
<td>0.022</td>
<td>0.018</td>
<td>0.019</td>
<td>0.03</td>
<td>0.013</td>
<td>0.018</td>
</tr>
</tbody>
</table>

radius average
0.023

Table 2: Anode row/column organized radius diameter for Anger camera test.

<table>
<thead>
<tr>
<th>Anger camera cluster radii</th>
<th>column 1</th>
<th>column 2</th>
<th>column 3</th>
<th>column 4</th>
<th>column 5</th>
<th>column 6</th>
<th>column 7</th>
<th>column 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>row 1</td>
<td>0.047</td>
<td>0.088</td>
<td>0.146</td>
<td>0.125</td>
<td>0.083</td>
<td>0.064</td>
<td>0.06</td>
<td>0.038</td>
</tr>
<tr>
<td>row 2</td>
<td>0.105</td>
<td>0.097</td>
<td>0.119</td>
<td>0.109</td>
<td>0.21</td>
<td>0.09</td>
<td>0.076</td>
<td>0.056</td>
</tr>
<tr>
<td>row 3</td>
<td>0.119</td>
<td>0.145</td>
<td>0.166</td>
<td>0.219</td>
<td>0.14</td>
<td>0.129</td>
<td>0.078</td>
<td>0.111</td>
</tr>
<tr>
<td>row 4</td>
<td>0.104</td>
<td>0.162</td>
<td>0.159</td>
<td>0.186</td>
<td>0.136</td>
<td>0.116</td>
<td>0.1</td>
<td>0.133</td>
</tr>
<tr>
<td>row 5</td>
<td>0.109</td>
<td>0.111</td>
<td>0.132</td>
<td>0.214</td>
<td>0.18</td>
<td>0.12</td>
<td>0.109</td>
<td>0.085</td>
</tr>
<tr>
<td>row 6</td>
<td>0.084</td>
<td>0.102</td>
<td>0.185</td>
<td>0.178</td>
<td>0.139</td>
<td>0.138</td>
<td>0.109</td>
<td>0.091</td>
</tr>
<tr>
<td>row 7</td>
<td>0.145</td>
<td>0.086</td>
<td>0.148</td>
<td>0.161</td>
<td>0.147</td>
<td>0.097</td>
<td>0.079</td>
<td>0.059</td>
</tr>
<tr>
<td>row 8</td>
<td>0.055</td>
<td>0.097</td>
<td>0.174</td>
<td>0.203</td>
<td>0.165</td>
<td>0.157</td>
<td>0.093</td>
<td>0.037</td>
</tr>
</tbody>
</table>

radius average
0.12
Figure 36: Row and column plots for weighted-summing board and Anger camera testing. A) Column plots for weighted-summing board. B) Row plots for weighted-summing board. C) Row plots for Anger camera. D)
Figure 37: Cf-252 flood exposure for 10,000 counts.
Vita

Matthew Walker Seals was born September 16\textsuperscript{th}, 1994, in Knoxville Tennessee to E.W. and Jamie Seals. He attended his undergraduate at the University Of Tennessee Knoxville for studies in Electrical Engineering. While attending undergraduate he worked as a research assistant to Dr. Dayakar Penumadu in his material science research group under the advisement of Dr. Stephen Young. Matthew’s focus as an undergraduate research assistant was on the development and design of non-destructive mechanical testing equipment. He went on to design and develop X-ray radiographic and tomographic user instruments with the help of Dr. Stephen Young as his advisor and Mr. Ken Thompson as head of the civil engineering machine shop.

Upon graduation, Matthew began his graduate studies in electrical engineering under Dr. Dayakar Penumadu and Dr. Benjamin Blalock at the University Of Tennessee. His graduate studies focused on electronics development for neutron detection methods optimized for neutron diffraction experimentation. He worked under the supervision of Dr. Richard A. Riedel at Oak Ridge National Laboratory on novel designs for Anger logic based spatially resolved neutron detectors.