Design and Performance of a Large Area Neutron Sensitive Anger Camera

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Abstract:

We describe the design and performance of a 157mm x 157mm two dimensional neutron detector. The detector uses the Anger principle to determine the position of neutrons. We have verified FWHM resolution of $< 1.2\text{mm}$ with distortion $< 0.5\text{mm}$ on over 50 installed Anger Cameras. The performance of the detector is limited by the light yield of the scintillator, and it is estimated that the resolution of the current detector could be doubled with a brighter scintillator. Data collected from small ($< 1\text{mm}^3$) single crystal reference samples at the single crystal instrument TOPAZ provide results with low values of the refinement parameter $R_w(F)$.

Keywords: Neutron detector, Anger Camera, Position sensitive detector, Single Crystal

1. Introduction

The Anger Camera first developed for the detection of gamma rays[1] analyzes the light distribution pattern from a scintillating material to determine the position of particle capture in the scintillator. This basic principle was extended for use in the detection of neutrons by using a neutron sensitive glass scintillator [2].

Like the first neutron Anger Camera, the neutron detector described in this paper uses enriched Li^6 glass as the scintillator. Improvements to the optics package and electronics of an earlier prototype of the detector [3] were made including the removal of an optical lens which introduced distortions into Bragg peaks and lowered the overall efficiency of the detector. The current design has FWHM resolutions that are reliably near 1.0mm. A least squares fitting method, similar to one described elsewhere [4], is used to determine the position of neutron capture in the scintillator, while new routines for gamma rejection and flat field corrections have been developed which improve gamma background rejection and the positional accuracy of the detector.

2. Design

The neutron Anger Camera has three major sub-assemblies: the optical front end, the preamp and summer stack assembly and the digital processing board assembly. The complete unit along with the major subsystems is shown in figure 1 and is described in more detail in the paragraphs below.

FIGURE ONE GOES HERE

2.1 Optical Front End.

The scintillator used in the Anger Camera detector is GS20 lithium glass from AST. The scintillator is selected at either 1.5 mm or 2.0 mm thick and is optically coupled to a 3.5 mm glass spacer that is optically coupled to an array of nine 64 element photomultiplier tubes (PMTs). The thicker scintillators are used in installations where enhanced neutron

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detection efficiency at low neutron wavelength is required. The scintillator extends slightly beyond the physical edge of the PMTs and provides an active area of 157 mm by 157 mm. Figure 2 shows a cross-section of this assembly. To improve the light collection, the top of the scintillator is painted with a white diffuse reflecting paint (Saint-Gobain BC620). The primary purpose of the glass spacer is to allow expansion of the light cone to span the tube gaps. As described in other designs, gaps between optically active elements have a major impact on the performance of the detector [5,6]. All glass interfaces are coupled using silicone gel. Because of the slight curvature of the glass window of the PMT a compliant gel “cookie” is also used at the glass spacer PMT interface. In general we find that the resolution is improved with decreasing spacer thickness. Tests with a higher light yield scintillator indicate the current configuration’s position resolution is light yield limited. (See appendix A)

FIGURE TWO GOES HERE

2.2 Single PMT processing electronics

Figure 3 shows the different electronic subsystems and how they are interconnected for a single photomultiplier tube. There are nine of these sections in a complete Anger Camera detector. For each phototube the original 64 pixels are transformed into 8 horizontal (x) and 8 vertical (y) values. The preamplifier, summer stack and A/D Conversion Electronic subsystems are described below.

FIGURE THREE GOES HERE

Preamplifier electronics: The preamplifier stage consists of 64 trans-impedance amplifiers. The trans-impedance feedback resistors are specifically chosen to compensate for the differences in the gains of the different phototube elements. The variation in gains of the 64 phototube elements can be as large as $\pm 50\%$ with a typical variation being $\pm 20\%$. The appropriate values of the feedback resistors are determined from data provided by the manufacturer.

Summing stages: The elements in each row and column of each tube are summed together using summing amplifiers. The outputs of the summing amplifiers are input into a gated integration stage and also to the discriminator electronics. The output of the integrator provides 16 signals (8 X and 8 Y) to the A/D convertor. By summing individual elements to create rows and columns the electronics is simplified considerably.

Conversion stage: Each of the row and column signals is delayed via a 200 ns delay line and feed into a 10bit pipeline A/D convertor. The time delay allows integration of the incoming signal to begin just before the rising edge of the signal. Each row and column signal is also feed into a simple threshold discriminator circuit (with hysteresis). The output of the discriminator and the A/D convertor are feed into a Spartan 3 FPGA.

1 The conversion electronics, discriminator electronics as well as digital communication
2 and timing links comprise what is known as an Anger camera Read Out Control (AROC)
3 board. Each Anger camera uses of nine of these boards, one for each PMT. Trigger
4 signals to and from each of the nine boards are used to synchronize the integration timing
5 and data collection over the entire detector array.

6 7 **2.3 Digital Processing Board.**

8 The nine AROC boards send digital conversion data to the Anger Camera Position
9 Calculation (ACPC) board. . The ACPC virtualizes the nine AROC boards so that the
10 system appears as one detector unit rather than nine. After receipt of conversion data
11 from all nine AROC boards, the ACPC then calculates the position of the detected
12 neutron. The ACPC board is also responsible for external digital communications, as
13 well as forwarding configuration and control data to and from the AROC boards. We
14 describe the data flow from the AROC boards to the ACPC as well as the position
15 calculation method in the following paragraphs.

16
17 2.3.1 Data Flow: Whenever a row or column signal exceeds the hardware
18 discriminator threshold in an AROC board, the AROC FPGA logic sets a global trigger
19 signal high. The other eight AROC boards use this signal to initiate data collection
20 timing. After a specified programmable delay (typically 2 ticks, where 1 tick=50ns) from
21 the trigger signal, the integrator gate of all nine AROCs are released starting the hardware
22 integration process. After m ticks (m is programmable), where m is typically 12, the
23 output of the integrator is captured. Thus, whenever any of the 144 (8 row plus 8 column
24 signals for each of 9 phototubes) signals trigger the hardware, 144 A/D conversion values
25 along with a timestamp are captured by the FPGA logic. Each AROC board
26 communicates the sixteen A/D conversion values it collects to the ACPC board.
27 The $9 \times 16 = 144$ values are used by the ACPC to calculate the neutron position. The first
28 step in the calculation is to remove the electrical offset, and to rescale the values to
29 eliminate variations in channel gain. The standard deviation of the channel gain is found
30 to be of the order of 4% and is due primarily to tolerance stack up in the electrical
31 components. These corrected 144 values are further reduced to 48 (24x and 24y) values
32 by summing the same row (y) values and the same column (x) values for each of the
33 three tubes. For example the first row from tube one (y_{11}) is added to the first row of tube
34 two (y_{12}) and the first row of tube three (y_{13}). This is the first of twenty-four y values
35 used for determination of the y position. This procedure is also done for the column
36 values. The summing of the initial 144 values in this manner provides 24x and 24y
37 values which when plotted as a function of row or column position provide the x and y
38 light cone cross-section or profile. These two sets of data provide the quantities used to
39 calculate the neutron position. Using separate x and y light cone profiles is justified if the
40 x and y variables are substantially independent. (This was confirmed with a special
41 pixelated setup which allowed a direct comparison of a true 2D fit versus two 1D
42 projections)

43
44 2.3.2 Position Calculation: The position of the neutron event is determined by
45 fitting a model curve to the measured data using a least square fitting routine [7]. The
46 reference curve is a two component Gaussian whose variance and relative weighting of

the components are determined beforehand as part of a calibration process. The general formula is $A(a_1 e^{-b_1(x-\lambda)^2} + a_2 e^{-b_2(x-\lambda)^2})$. A two component Gaussian is used because it can fit the general shape of the light distribution which we find to be a narrow central peak having a broad baseline. The mean position (λ) and amplitude (A) of the model curve are allowed to vary to minimize the sum of the squares of the difference between the measured light cone profile and the reference curve. a_1 , a_2 , b_1 , and b_2 are fixed quantities determined beforehand. How these constants are determined is discussed in the following section. This position calculation method has been used elsewhere.[4] It was shown in that case, and is confirmed by our own results, that positioning errors are reduced (especially at the detector edges) when using the least squares method over a simple centroid. Figure four illustrates a typical response that is fitted by the process. 4a is an image of a typical light cone, while figure 4b and 4c show the cross sections, x and y respectively, that are fitted by the process. The diamonds represent the response of a row or column of the phototube and only five points are used in the minimization process. We note that if the variance of the reference curve is allowed to vary during the minimization process; the resolution and distortion are found to be worse than if the variance is fixed.

FIGURE FOUR GOES HERE

2.4 Reference Curve: The reference curve is determined by measuring the light cone from multiple neutron events (typically 1000) and averaging the results. The shape of the average light cone is then used to determine a set of appropriate fitting function parameters. Important in the design of the Anger Camera is the width of the light cone, which determines the extent to which a particular set of optics can bridge the gaps between phototubes. When too narrow the distortion is made worse, when too broad the resolution suffers. Figure five shows the measured light cone (diamonds) along with predicted results from a simple Python simulation. The discrepancy in the tail region is probably due to the lack of the inclusion of multiple reflections in the simulation. The two simulation curves are at the extremes of the optical path lengths, 6.5 mm (square) being from a neutron detected at the top of the scintillator while the second (triangle) is for an event occurring at the bottom of the scintillator. The primary Gaussian component of the model equation of section 2.3.2 has a standard deviation (related to b_1) of about 6 mm while the second broader Gaussian of the model equation has a standard deviation (related to b_2) of about 13 mm. The weighting factor of the two components is 3 to 1 respectively (a_1 and a_2 of the reference equation). We find that the standard deviation of the reference curve is substantially independent of the specific location the data is collected from including data collected from the gap regions. The reference curve parameters are also found to be the same for the x and y dimensions.

FIGURE FIVE GOES HERE

3. Performance

In the sections below we describe the results of a number of performance tests done on the Anger Camera. The results presented are representative of a larger body of testing done on over fifty detectors. Three critical parameters, resolution, distortion and uniformity were tested in more than one way as part of a quality assurance (QA) plan prior to installation and as part of an in-situ test at an SNS beam line. The QA tests are performed on all detectors at the CG1A test beam line at HFIR facility. The QA tests use a monochromatic beam of 4.2 Å having a beam divergence of about 0.5 degrees. Further details of the QA test are described in the sections below. The in-situ tests were performed at the TOPAZ beam line at the SNS facility. The wavelength band for the in-situ tests was 1.0 Å to 4.0 Å. A polyethylene sphere of 3mm diameter was the scattering sample and a variety of different masks were used depending upon the variable of interest. Details of the in-situ tests can be found in the sections below. We should note that the in situ tests are labor intensive and take a considerable length of time (2 weeks) to obtain the necessary statistics for analysis and are therefore not routinely done. However, the development of an in situ test method is important to determine the detector's performance after installation. Data from both these test methods are presented in the resolution and distortion sections. In addition to the performance testing results, we describe in the sections below the sliding photosum and flat field algorithms. Determination of the data sets for use in these algorithms is part of the calibration procedures that are needed for optimal operation of the detector and are calculated from an in-situ (i.e. at the instrument) flood measurement.

3.1 Count rate and efficiency.

While the short scintillation time of the GS20 glass provides a basis for a detector capable of near 1MHz count rates, we find the rate capability much more limited in this detector. It is known the count rate is limited by the FPGA firmware to about 20 KHz. To gauge the exact rate performance of the Anger camera, we compared its count rate to that of a fission monitor having an efficiency of about 10^{-3} . Measurements of the count rate linearity were made at the CG1A beam line at HFIR. The incident neutrons were monochromatic with a wavelength 4.2 Å. To limit any variability from beam divergence (0.5 degrees), a 2.5cm x 2.5cm aperture was placed in front of the detectors under test. The neutron flux was modified using a combination of neutron attenuators and different slit widths. Figure six shows the count rate of the Anger Camera detector versus the fission monitor. No rate loss is seen up to a count rate of 15 KHz with a 3% rate loss seen at 18 KHz. While considerably lower than the theoretical maximum count rate, this rate is not a limitation for use on the diffraction instruments where the maximum peak count rate on a detector is <10 KHz. Firmware changes are expected to increase the maximum count rate to approximately 80 KHz. To measure the efficiency of the Anger Camera, we compared its count rate to a ^3He proportional counter. The ^3He detector contains 10atm of ^3He and has a diameter of 2.5cm. The Anger Camera and ^3He detector were both placed in turn behind a 1cm x 1cm aperture. The count rate for the measurements was about 2 KHz. Referenced to the ^3He detector, the efficiency of the Anger Camera is found to be $93\% \pm 2\%$ at 4.2 Å.

FIGURE SIX GOES HERE

3.2 Influence of the Optical Gaps.

The optically inactive regions that exist in the detector have a significant impact on the pre-corrected positional accuracy of the detector. The effect of these regions can best be seen by examination of an uncorrected flood image (Figure 7a). The optically dead regions are located at the tube gaps near 170 and 340 pixels and are characterized by a large apparent variation in total collected counts as a function of position. (Much smaller optically dead regions also occur between the individual anode elements in a single PMT). While the variations in uniformity of a flood field image can be dramatic they are not primarily due to variations in detector efficiency. Scans through these regions indicate that the detector efficiency is constant within $\pm 3\%$. The large variations seen in the flood pattern are due to errors in the neutron position assignments. While the position varies only slightly between the individual PMT pixels, the error becomes large near the PMT gaps. Simulations show that the position error can be as large as 0.5mm to 0.7mm across the gap. This behavior is straight forward to simulate and we find good correlation between experiment and the simulation predictions [8]. Figure 7b shows the results of a Python simulation of the expected detector response to a flood image. The presented data is a horizontal intensity profile. The dramatic increase in intensity near the tube gaps is clearly seen as well as the smaller modulation in the intensity near each individual PMT anode element.

FIGURE SEVEN GOES HERE

3.3 Flat Field Correction:

To correct positional errors caused by the optically inactive regions, a flat field algorithm is used. It achieves the desired goal of eliminating a significant amount of the distortion seen in an uncorrected flood field measurement. The assumption of uniform counting efficiency forms the basis for the correction. Measurements have shown that, except near the detector edges, this is a valid assumption. If this is the case, then variations in apparent rates are due to the mapping of smaller or larger detector areas onto a constant area pixelization map (we denote this constant pixelization area as Δ^2). For example points with larger or smaller apparent count rates come from an area $A = (1.0+p)\Delta^2$, where p is the fractional increase or decrease from the average local rate. If we describe the average dimension as $\Delta^2=xy$ then $A=(1.0+p)xy$. This can be extended to the complete set of m by n pixels where $A_{mn}=(1.0+p_{mn})xy$, and m and n run over the same integer set from 0 to $d-1$, where d is the total number of pixels along x or y . The correction problem is equivalent to finding new x'_n and y'_m such that $x'_n y'_m = A_{mn}$. This is an underdetermined system having $2d^2$ unknown parameters, i.e., x_n and y_m at each point. There are only $d^2 + 2d$ constraints, e.g., the d^2 products of $x'_n y'_m$ and the physical length constraints of $\sum x'_n = L$ and $\sum y'_m = L$. To produce a correction table we assume that one of the dimensions does not change. For example when determining the variations in x along a row, we assume the y dimension is constant. The average dimension is determined by using a slowly varying averaging function near the row being solved. This is not exactly true and leads to residual errors in the flat field image. Two correction tables are created that provide correction shifts in the x and y dimensions prior

1 to pixelization for each neutron event. Figure 8 shows a typical flood field image after
2 flat field correction. To improve the distortion in areas where four detectors meet at their
3 corners (four corners region), more complicated self-consistent algorithms are under
4 investigation.

5
6 **FIGURE EIGHT GOES HERE**
7

8 **3.4 Gamma Discrimination:** In GS20 glass there is little to no variation in pulse shape
9 between gammas and neutrons. One must therefore rely entirely on pulse height
10 discrimination to distinguish between the two. In this detector the pulse height, which is a
11 measure of the energy deposited in the scintillator, is measured by the photosum. The
12 photosum defined as the sum of all 24 light cone profile values measured along an axis
13 (the x and y photosums are approximately equal) is directly related to the light yield of an
14 interaction in the scintillator. When neutrons interact in the GS20 scintillator they have a
15 known light yield which can be seen as a relatively narrow peak in the photosum
16 spectrum. In figure 9a, we plot the photosum value in a small 3mm by 3mm region near
17 the middle of the detector. The measurement was performed at TOPAZ using a small
18 3mm polyethylene sample. The data is the integration of detectors counts over a
19 wavelength band from 1 Å to 4 Å . The peak near 2200 is due to scattered neutrons. The
20 small baseline (dashed line in figure 9a) and the peak near 500 are primarily due to
21 gammas, with the peak near 500 due to gammas generated by ^{10}B in the surrounding
22 shielding. The contamination to the neutron signal due to gammas under the neutron peak
23 near photosum 2200 is about 0.5%.

24 Gamma discrimination is accomplished by accepting only those events whose photosums
25 are within the neutron peak. The PMT gaps complicate this simple method of gamma
26 discrimination. Because of the optically inactive region at the tube gaps we expect less
27 light to be collected when an interaction occurs in the scintillator near these positions.
28 The neutron peak seen at 2200 in figure 9a will therefore be at a small value for neutrons
29 detected at the gap positions. This variation in photosum can best be seen in figure 9b
30 which is a plot of the mean value of the neutron peak as a function of position in the
31 detector. Here one sees the large variation in the value of the neutron peak, varying from
32 near 2200 at tube center to about 1500 in the regions where the corners of four detectors
33 meet. The substantial variation of the neutron photosum peak as a function of position
34 requires, for the best gamma discrimination, acceptance limits that vary with position.
35 This practice of first determining the position before a determination is made as to
36 whether the event is due to a neutron or not is referred to as the sliding photosum method.
37 The use of variable or sliding photosum limits substantially reduces the background seen
38 by the Anger Camera. Multiple measurements done at the TOPAZ beam line, at many
39 scattering angles, show that the sliding photosum method gives a threefold improvement
40 in the signal to noise compared to using fixed acceptance limits.

41 To provide a general gamma discrimination figure of merit, we measured the detector's
42 response to two different gamma sources: a ^{137}Cs source of strength 2.2uCi and a ^{60}Co
43 source of 1.5uCi. The sources were placed 170mm from the face of the detector and the
44 detector count rate was monitored with and without the source present. For ^{137}Cs the
45 rejection factor was better than sensitivity limit of the test or 2.0×10^{-6} . For ^{60}Co it is
46 about 4.0×10^{-5} . While this measure of gamma sensitivity is useful, it does not present

1 the entire picture of gamma discrimination for this type of detector. The actual
2 contamination due to gammas will be considerably smaller when used at a time-of-flight
3 (TOF) diffraction instrument. At a TOF instrument events of interest are limited in both
4 time and position thus providing significant additional discrimination as neutron events
5 are relatively concentrated in a short time interval and gamma events are more uniformly
6 distributed in time.

7
8
9 FIGURE NINE GOES HERE

12 **3.5 Magnetic Field Behavior.**

13 PMT based detectors are known to be sensitive to magnetic fields. To ensure the Anger
14 Camera could tolerate the allowed stray field specification at SNS (5 gauss) we fashioned
15 a three axis Helmholtz coil to investigate the behavior of the Anger Camera in a magnetic
16 field. The three axis coil was placed over the optical head of the Anger Camera and a
17 borated aluminum neutron mask with holes at various positions, specifically at the tube
18 gaps and tube centers was placed on the face of the detector. The detector's response
19 when exposed to a ^{252}Cf source was recorded. A gauss meter recorded the magnitude of
20 the magnetic field as well as its direction. The field could be varied up to a maximum of
21 25 gauss. We find that the detector is only sensitive to a magnetic field perpendicular to
22 the face of the detector, and that only regions near the horizontal tube gaps are affected.
23 Fields up to 25 gauss along the other two axes had no measurable effect on the detector
24 response. From tests using an active compensation coil to null out the external field, we
25 find that to the extent the perpendicular field is uniform it is possible to actively
26 compensate for its influence. Figure 10 shows the images of the response of the detector
27 with no magnetic field (10a) and of the detector response with a 25 gauss magnetic field
28 (10b) perpendicular to the detector face (z direction). There is both a drop in photosum
29 in regions near the horizontal tube gap as well as a shift in the position of the mask hole.
30 The loss in photosum has a dramatic effect near the top of the detector where the loss of
31 response in the phototube causes the signal to fall below the electronic discriminator
32 threshold. The shift in position can be attributed to the preferential loss of signal on one
33 edge of the phototube. This causes a shift in position toward the less affected edge. We
34 find that operation in magnetic fields with a component perpendicular to the detector face
35 of greater than 10 gauss is not recommended. This test was performed on a single
36 representative detector but similar behavior is expected on any of the Anger Cameras.

37
38 FIGURE TEN GOES HERE

41 **3.6 Position Resolution**

42 Two methods were used to determine the resolution of the detector. The first method
43 uses a small mask consisting of four 0.5mm slits and nine 2.5 mm holes (QA mask). The
44 mask is made from 2mm borated aluminum and adsorbs > 99% of incident neutrons at
45 4.2 Å. Figure 11 a shows the detector's response to this mask at one position. Resolution
46 measurements using the QA mask were done at the CG1A beam line at the HFIR facility.
47 The characteristics of the neutron beam at CG1A were described earlier. The typical

count rate for this test was 4 KHz. The QA mask was held stationary while the detector was stepped behind it in 4 mm increments. From this scan an array of 28 horizontal by 28 vertical or 784 data sets was collected. With the four slits (two vertical and two horizontal) a total of more than 3000 resolution data points was produced. The resolution was determined by a sum of squares of all the individual resolution data points. FWHM position resolutions measured by this test typically range from 1.1 mm to 1.2 mm. Figure 11b shows the position resolution measured by one of the vertical slits (784 total data points) at various positions of the detector. The x and y axis units of figure 11b are in terms of steps which correspond to the aforementioned 4mm step increments. The resolution is noticeably different in two horizontal strips near y step nine and y step twenty in the figure. These strips occur at the positions of the horizontal gaps between the phototubes. The resolution in the gaps is expected to about 20% poorer than the regions near the center of the phototubes because of the lower total light in the signal. A second test using a resolution mask that can be used for tests in-situ (at the TOPAZ beam line) confirms the QA test results. The resolution mask used for the in-situ test consists of a 5mm thick borated aluminum plate with sets of line patterns of differing width. This mask provides the modulation transfer function of the detector. Figure 11 c shows the response of a detector to this mask. Rather than a monochromatic neutron wavelength the in-situ test uses band of neutron wavelengths from 1Å to 4Å. Figure 11d is the vertical cross section of the detector response shown in figure 11c. The cross section is used to calculate the modulation for each of the line pair widths. The line width value where modulation equals 0.5 provides a good estimate of the FWHM resolution of the detector. Typically, the in-situ measurements give FWHM position resolutions of 1.0 mm to 1.1 mm. We also calculated the position resolution for three narrower wavelength bands (1.0Å in width) centered at 1.5Å, 2.5Å and 3.5 Å and within experimental error we find the position resolution to be independent of wavelength.

FIGURE ELEVEN GOES HERE

3.7 Distortion

Distortion or positional accuracy is an important parameter that is not always reported. In the Anger Camera detector distortion must be reported along with the resolution because improvements in resolution can cause an increase in the distortion. We find the distortion is very small except near the tube gaps. This behavior is also seen in simulations of the detector response. [8]. Distortion errors seen in uncorrected images are reduced by the use of the flat field algorithm described previously. All data presented in this section is flat field corrected data. Distortion was measured as part of the detector QA testing and was additionally measured in-situ at the TOPAZ beam line. When measured as part of the detector QA, data is collected using the same mask (figure 11a) that was used during the resolution measurement. Conveniently the same data set is used for both the resolution and distortion measurements as well as uniformity. To determine the distortion, the mean x and y position of the center hole is estimated at each measurement step (784 total data points) using a standard method [9]. The position error

at each of the 784 measurement points is calculated from linear regression fits for each row and column. Figure 12a shows a 2D plot of the x dimension positional errors of a typical detector. The standard deviation (σ) of the residuals for x and y dimensions are also calculated and the 3σ population estimate is the actual number reported for a detector. A typical 3σ is $<0.3\text{mm}$. The QA acceptance criteria of having a 3σ residual value of $<0.5\text{mm}$ is met in over 95% of the detectors tested.

A corroborating test for distortion was also made at the beam line. For the in situ test a fiducial mask (1.0 mm holes separated by 9.0mm) is used. (See figure 12b). As we previously described, the distortion is found from the position residuals of a linear best fit to the mean positions of the holes.

The in situ distortion masks were placed at two different positions on the detector. The 3σ population estimate from all measured points is the reported distortion value.

The 3σ value for thirteen detectors measured in-situ ranged from 0.3mm to 0.4 mm, with one detector at 0.5mm. In practice we find that the 3σ value is very close to the maximum error in the population. This finding is useful when examining 2D plots such as figure 12a as it indicates there should be no distortion error much greater than 0.5mm for a qualified detector.

FIGURE TWELVE GOES HERE

3.8 Uniformity

We have shown how the mask of figure 11a is used to measure the resolution and distortion. It is also used to measure uniformity. Because the QA test is done by stepping the detector behind the mask, the incident beam flux is constant thus providing a convenient method to measure uniformity. This is done by measuring the variation in the background subtracted counts in the center hole of the QA mask as a function of position. The measurement time for each step point is long enough to provide at least 10,000 total counts in each of the nine holes of the QA mask. Uniformity is calculated as the fractional difference in counts from the population average. We find that 90% of the detectors tested have uniformities better than $\pm 3\%$. Figure 13a and figure 13b show the results of a typical uniformity measurement. Both figures are plots of the same 784 data points. Note the lack of any “gap” features in figure 13b that were seen in the resolution figure 11b, indicating that the count rate is unaffected by the gap structures. To explicitly verify that the PMT gaps have no effect on the count rate, we performed a second hole scan where the hole is scanned diagonally across the detector through the center of the four corners region. We know this is the area of maximum light yield loss. In the uncorrected flat field image (figure 7a) the apparent variation near this region is as large as $\pm 30\%$. Figure 13c and 13d show the results of the count variations through one of the four corners gaps. Figure 13c shows the relative change in count rate. The count rate at the center of the four corners gap is found to be the same, within measurement error, as the PMT center. These results confirm that the variations seen in uncorrected flat field are due to position distortions and not count rate variations. This subtlety is important to recognize as it indicates that using the uncorrected flat field to normalize count rates of experimental data on a pixel by pixel basis is incorrect.

FIGURE THIRTEEN GOES HERE

3.9 Performance at Instrument:

While details about the behavior of the detector are interesting from a design standpoint the behavior of the detector when installed is even more critical when evaluating a potential detector for experimental use. This is especially true when many detectors must be built and installed, requiring uniformity in construction and performance that in some designs can be difficult to achieve or maintain. For example a typical single crystal experiment may last many days and contain reflections from thousands of Bragg peaks with many of the reflections being measured on multiple detectors. Accuracy in the determination of peak centers and the integrated intensity are critical in obtaining good quality data and because the statistical set of data is large during a single crystal experiment, it provides a good corroborating measure of detector performance. As part of the commission phase of instrument operation, experiments using a set of standard samples are done to assess whether an instrument is ready to be admitted into the user program. The single crystal instrument TOPAZ recently undertook these experiments and achieved very excellent results as represented by refinement parameters, especially $R_w(F)$ which is a typically figure of merit for crystallographic studies. For a set of three standard samples all of about 1mm^3 in size, the $R_w(F)$ was determined to be approximately 0.03-0.04 [10]. These low R_w values along with low root mean squared errors of the atomic displacement parameters (ADP) show that the detectors more than meet the instrument performance requirements. Recently even lower $R_w(F)$ values have been achieved on even smaller samples[11].

4. Summary

We have described the design of a large area neutron Anger Camera suitable for use in many neutron scattering applications. The presence of optically inactive regions between the PMTs creates difficulties in the design requiring some compromise in the performance characteristics. In spite of this difficulty, more than 50 Anger Cameras are in use at the SNS and all meet the following performance criteria.

- 1) Average position resolution $< 1.2\text{mm}$ (FWHM).
- 2) Distortion residuals $3\text{s.d.} < 0.5\text{mm}$.
- 3) Uniformity variation $< \pm 4\%$

We find that the performance of the current design could be improved considerably if a large area neutron sensitive scintillator with higher light yield could be found.

Appendix

In this appendix we examine the effect of the light cone spread on the position resolution of the Anger Camera. Qualitatively we would expect the resolution to improve with a narrower light cone. This can be argued because the slope of the Gaussian is larger for a substantial part of the curve which makes the least square fit less sensitive to variations in the magnitude of the fitting points. This behavior can be seen in figure 14 (squares) where we plot the position resolution for a variety of light cone widths. The scintillator used was GS20 glass. The width of the light cone is modified by changing the thickness of the spacer glass. We see a substantial change in the resolution as the light cone width

changes. The total number of photons collected is approximately constant for this test, so there is little change in Gaussian noise. Because (as was noted elsewhere [6] and confirmed by our tests) resolution and distortion are coupled, we cannot simply reduce the light cone spread to improve the resolution. While a narrower light cone does improve the resolution, it also worsens the distortion especially near the tube gaps. When this distortion becomes very large, it becomes difficult to correct using the flat field correction algorithm. If one could reduce or eliminate the tube gaps, then one could certainly improve the resolution without compromising the distortion. We can also examine the effect of higher light yield scintillators by using a LiF/ZnS scintillator. Although the scintillator is a white opaque material, adjustment of discriminator settings and the phototube high voltage allows one to select neutron events emitted near the back of the scintillator that are bright enough so that the quantum noise is very low. The resolution versus the light cone width using the LiF/ZnS scintillator is also shown in figure 14 (diamonds). Unlike the GS20 scintillator results, the resolution is constant as a function of light cone width. We estimate that the light yield for the collected neutrons is about ten times that of the GS20 glass. The LiF/ZnS results provide an estimate of the resolution limit of this detector system. If we remove the contribution from the test slit, the results indicate that the resolution of the current design could be more than doubled (nearing 400um resolution) with a higher light yield scintillator. In addition to improved resolution, the pre-corrected distortion of the detector would also be reduced. It should be noted that only about one to two percent of the neutron captures in the LiF/ZnS had a light yield suitable for this study.

FIGURE FOURTEEN GOES HERE

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References

- [1] H.O. Anger "Scintillation Camera", *Review of Scientific Instruments*, vol 29 No. 1, pp 27-33, (1959)
- [2] M.G. Strauss et. al.. "2-D Position-Sensitive Scintillation Detector for Neutrons", *IEEE Transactions on Nuclear Science*, vol 28 , pp 800-806, (1981).
- [3] J.D. Richards et. Al. "Development of a Neutron-Sensitive anger Camera for Neutron Scattering Instruments", *IEEE Transactions 2010 Nuclear Science Symposium Record* pp 1771-1776 (2010)
- [4] De Lurgio et. al, "2-D Scintillation Position-Sensitive Neutron Detector" *IEEE NSSC Record* N14-129. (2005)
- [5] G. Kemmerling, et.al , "A new two-dimensional scintillation detector for small angle neutron scattering experiments," *IEEE Trans. Nucl. Sci.*, vol. 48 no. 4, pp 1114-1117, (2001).
- [6] J. Schelten et. al., "Development of a Linear Position-Sensitive Neutron Detector", *Nuclear Instruments and Methods*, vol 205, pp 319-330 (1983).

[7] We employ a Levenberg-Marquardt procedure using methods similar to those found in C Numerical Recipes in C, Second Edition, pp 685-687 (1992)

[8] R.A Riedel et. al. “Resolution and Accuracy Limitations in a Large Area Neutron Sensitive Anger Camera” NSS/MIC Nov. 2012.

[9] We use a Gaussian fitting function and the leastsq subroutine from the SciPy library.

[10] A. J. Schultz et. al. “Integration of neutron time-of-flight single-crystal Bragg peaks in reciprocal space”, J. Appl. Crystallography, vol 47, pp 915-921 (2014).

[11] M. R. V. Jørgensen et. al., “Accurate Atomic Displacement Parameters from Time-of-Flight Neutron Diffraction Data at TOPAZ”, Acta Crystallographica A

Figure Captions:

Figure 1 Showing a complete Anger Camera Assembly. The “snout” on the right contains the optics package and preamp electronics. The signal processing boards are also visible within the body of the detector.

Figure 2 shows a cross-section of the Optics Package. Starting at the top of the optics package we have a white reflector with the scintillator just below (also white in appearance). Just below the scintillator is a glass spacer (dark in color) which is optically coupled to the phototubes that are the three grey units just below the glass spacer. Note the gaps between phototubes. These optically inactive gaps are about 4mm wide and not only reduce the number of photons collected from a scintillation event, they cause errors in the position calculation which must be corrected.

Figure 3 showing the signal flow of the Anger camera. The diagram represents one of nine conversion components denoted as AROC boards in the text. Trigger signals are used to synchronize data collection across the nine conversion electronic (AROC) boards.

Figure 4 showing details of the position calculation method. The x and y axis units are row and column pixels, with each pixel having a dimension of about 6 mm. 4a is an image of the light cone. 4b is the x profile and 4c is the y profile. The profiles are obtained by summing over the alternate dimension.

Figure 5 showing the measured light cone along with simulated results for neutrons detected at the front and the back of the scintillator. The simulation includes light reflected from the back of the scintillator.

Figure 6 showing the rate response of the Anger Camera. The dashed line is the linear extrapolation of the best linear fit of the data points up to about 15Khz.

Figure 7 showing the uncorrected flood field image of the neutron detector. (a) The image artifacts that delineate the optically dead areas of the detector are clearly visible. The results of a simulation are shown (b). The same behavior at the tube gap regions near 170 and 340 pixels is clearly seen in the cross-section.

Figure 8 showing typical corrected flood field image. This should be compared with the image of figure 7a. Near the four corners regions, there remain some residual uncorrected distortions.

Figure 9. The mean value of the neutron photosum at different positions of a detector (9b). The photosum spectrum from a small center region is shown as the solid line in figure 9a. The two peaks are due to neutrons (photosum $\approx$ 2200) and boron gammas (photosum $\approx$ 500). The dashed line indicates a quadratic fit of the background. The colorbar scale is in photosum arbitrary units but having the same magnitude as the horizontal scale in 9a .

Figure 10. The magnetic field dependence of the anger camera. (a) no field. (b) 25 gauss field perpendicular to the detector face. The widening of the horizontal gap regions is clearly seen.

Figure 11 (a) shows the detector response from a slit-hole QA mask. (b) shows the resolution as a function of position for one of the vertical slits. (c) Shows the detector response from an in-situ resolution mask. Each set of five lines has a specific width and separation starting at 1.5mm at the top and being reduced by 0.25mm until they reach 0.5mm at which point they return to 1.5mm. (d) shows the cross-sectional plot for the response. In figure 11c.

Figure 12 showing the x position errors (a) as measured by the QA mask described in the text. The calculated RMS error is 0.14 mm. The detector's response to an in-situ hole mask is shown (b).

Figures 13. Representative variations in count rates of the Anger camera. In 13a we show the results of all 784 scanning points described in the text. In b these values are plotted in a 2D color plot. In 13c we plot the variation in count rate from a scan through the four corners region of a detector. The center of the four corners gap is at about -20 of the horizontal scale in figure 13c (x=340, y=340 in figure 13d). No large loss of count rate is seen at the gap center. Figure 13d shows the measurement spots on the detector for the scan. The spot at the upper most right position of figure 13d corresponds to the left most measurement point (near -47) in figure 13c.

1
2
3 Figure 14 showing the position resolution of a 0.5mm slit has a function of light cone
4 spread. The contribution to the resolution from the 0.5mm slit has not been removed.
5 The squares show the response when using a GS20 scintillator. The diamonds show the
6 response when using a ZnS/LiF scintillator. The discriminator and PMT high voltage
7 were set such that events from the ZnS/LiF test had approximately 10 times the light
8 yield of the GS20 test. The ZnS/LiF test indicates that resolution could be significantly
9 improved with a brighter scintillator.

figure 1

figure 2

figure 3

figure 4

figure 5

figure 6

figure 7

a

b

figure 8

figure 9

figure 10

figure 11

figure 12

figure 13

a

b

c

d

figure 14