Final Report

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Contents

1 Introduction

This summer, I had the opportunity to take part in several different projects. Most of my work involved computer simulations using the GEANT software, but I had the chance to gain some experience with detection hardware both here and at Duke University.

2 Compton Scattering

Using GEANT software, I investigated the use of atomic Compton scattering as a means to determine the flux of gammas in a beam. The gamma beam passes through a thin copper plate, where Compton scattering occurs. The resulting particles then proceed to detectors which are used to determine whether or not Compton scattering has occurred. There are three detectors in the setup, two of which are used to detect electrons and gammas from Compton scattering, and one which is placed in the beam line. After initial calibration, in which the Compton event to beam flux ratio is measured, the on-axis detector can be removed and the beam flux determined through the two detectors remaining.

2.1 Overview

The set up of this experiment involves three detectors, which are placed in air. Each detector consists of a cylinder of sodium iodide (NaI), with length and diameter 25.40 cm, encased in aluminum, which was 0.64 cm thick except on the face of the detector, where it was 0.16 cm thick. There was an NE102 detector placed in front of the NaI, which was 0.32 cm thick and 26.68 cm by 26.68 cm. Each detector had with it an iron collimator, 26.68 cm by 26.68 cm on the face and 10.16 cm thick, with an inner diameter 17.78 cm. The collimators were placed 0.50 cm in front of the NE102 detectors.

A copper target, 0.16 cm thick and 5.00 cm by 5.00 cm on the face, was placed in the beam line. The effect on the results of changing the copper plate to 0.32 cm thickness was also investigated briefly.

The beam spot intensity distribution was a clipped Gaussian, with sigma equal to 5.0 cm, but clipped to a 1.25 cm radius. The beam passed through the copper target and on to the on-axis detector. Gamma energies of 10 MeV and 5 MeV were both tested.

The other detectors were situated to determine if Compton scattering had occurred. In the case of 10 MeV incident gammas, the gamma detector was arbitrarily placed 3.00 m from the copper target, and 10 degrees from the beam line. The electron detector's angular position was then determined from the Compton scattering formula and from the relativistic kinematics of the interaction. With an initial gamma energy of 10 MeV, this angle was determined to be 29.1 degrees from the beam line. The distance from the copper plate to the electron detector was varied from 0.50 m to 3.00 m.

In the case of the 5 MeV incident gammas, it was impractical to place the gamma detector at 10 degrees from the beam line, as this setup would cause the scattered electrons to have an energy of less than 1 MeV. At this energy, it becomes increasingly unlikely that electrons reach and are detected by the detector. Instead, three different setups were tested. The gamma detector was placed 3.00 m from the copper plate and 17.0, 21.3, and 26.1 degrees from the beam line for the different setups. These different placements for the gamma detector corresponded to electron detector placements of 42.8, 33.0, and 26.1 degrees, respectively. Again, the distance from the copper plate to the electron detector was varied from 0.50 m to 3.00 m.

2.2 Procedure

Two methods were employed in particle detection and identification. One method took advantage of the internal tracking in GEANT to make positive identification of particles. It registered a Compton event when an electron and a gamma hit their respective detectors and deposited some energy, and at the point at which they hit the detectors, had combined energy within 2 MeV of the initial gamma energy (the 2 MeV range was given to allow for energy losses in the air and the copper).

The other method made particle identification based on the amounts of energy deposited in the NE102 and NaI detectors. In the 10 MeV case, a particle was identified as an electron if it deposited at least 0.43 MeV in the NE102 detector and less than 2.5 MeV in the NaI. For particles to be identified as gammas, they must have deposited less than 0.43 MeV in the NE102 detectors and more than 2.5 MeV in the NaI detectors.

In the 5 MeV case, different energy cuts were needed to reflect the different kinetic energies of the electrons. For the gamma detector placement of 17.0 degrees, a particle was deemed to be an electron if it deposited at least 0.52 MeV in the NE102 and less than 0.5 MeV in the NaI. For the gamma detector placement of 21.3 degrees, a particle was deemed to be an electron if it deposited at least 0.48 MeV in the NE102 and less than 0.75 MeV in the NaI. For the gamma detector placement of 26.1 degrees, a particle was deemed to be an electron if it deposited at least 0.46 MeV in the NE102 and less than 1.5 MeV in the NaI. If a particle failed both of the criteria, it was deemed to be a gamma.

The threshold levels for the detectors were determined from test runs conducted with a single detectors, and particles of the appropriate type and energy (calculated from the Compton scattering formula) aimed straight at the detectors. This gave results of typical amounts of energy deposited in each of the detectors by the particles.

A Compton event was detected when, during one trigger, a single particle hit both the electron and gamma detectors, and passed the conditions of the two different methods. Records were kept of the number of Compton events detected using both methods, as well as the delta E and E measurements of the particles which were detected in these events.

As well, all particles which hit the electron and gamma detectors were counted and their delta E and E data plotted in histograms. The count rate at the on-axis detector was also determined, to be used to determine the relationship between the number of Compton events detected and the beam flux.

The electron detector was placed at different distances from the copper plate, and the results of 10,000,000 trigger runs were recorded. The distances varied between 0.50 m and 3.00 m.

2.3 Results

It was determined that, for an initial gamma energy of 10 MeV, an electron detector placement 0.50 m away from the copper plate was the most efficient at detecting the Compton events. At this distance, it detected 2.3 events per million incident gammas (using either method of detection). Doubling this distance, the count rate dropped to 1.2 events per million incident gammas. Distances farther than 1.00 m provided less than 1 event per million incident gammas.

It should be noted that the angle subtended by the gamma detector face at 3.00 m is approximately 3.4 degrees. The angle which should have contained the corresponding electrons was 8.6 degrees. This means that the electron detector should have been placed 1.18 m from the copper plate. However, due to scattering of the electrons in the air and in the copper plate, a placement of 0.50 m provided a much larger count rate, which appears to have been optimal.

For an initial gamma energy of 5 MeV, an electron detector placement 0.50 m from the copper plate, at an angle of 42.8 degrees (corresponding to a gamma detector angle of 17.0 degrees) provided an optimal count rate. It gave a rate of 1.4 events per million incident gammas. The next highest rate available in any of the setups was 1.0 events detected per million incident gammas, with the electron detector placed at 0.50 m and 33.0 degrees from the beam line (corresponding to a gamma detector placement of 21.3 degrees). It should be noted that when the electron and gamma detector were both placed at 26.1 degrees, and the electron detector was 0.50 m from the copper plate, the detector interfered greatly with the gamma beam.

When the 0.16 cm copper plate was used, the number of gammas passing through to the on-axis detector was approximately 9,360,000, per 10,000,000 events. So, the absorption factor of the 0.16 cm copper plate was 6%.

Changing the thickness of the copper plate increased gamma beam absorption. Only approximately 8,960,000 gammas per 10,000,000 passed through and hit the on-axis detector, increasing the absorption to 10%.

The count rate of Compton events when the copper plate was changed to 0.32 cm was 1.2 events per million, when the detector was placed 1.00 m away from the copper plate. This is similar to the count rate when the copper plate was 0.16 cm thick.

2.4 Conclusions

If this method of monitoring a beam flux were to be used, it would be most efficient for a beam energy of 10 MeV to have a copper plate of thickness 0.16 cm, and an electron detector placed 0.50 m from the copper plate, at 29.1 degrees. For a beam energy of 5 MeV, it would be most efficient to have the electron detector placed 42.8 degrees from the beam line and 0.50 m away from the copper plate, and the gamma detector placed 3.00 m away from the copper plate, at 17.0 degrees.

3 Duke University Trip

From June 29th to July 5th, we traveled to Duke University to assist in an experiment running at the High Intensity Gamma Source at the Free Electron Laser Lab. While at HIGS, I assisted in several areas of the experiment.

I helped lower the threshold levels on the CF-8000 modules. This allowed signals with smaller peak energy to be recognized in the electronics, and increased the number of neutrons we could ‘see’. Also, I helped adjust the gains on the photomultiplier tubes. We needed to ensure that these all had the same voltage to maintain consistency in detecting the neutrons. As well, I monitored the beam flux, and started and stopped runs. The runs were usually started after the people in the control room had re-injected electrons and the beam flux was sufficient. The runs were ended when the flux dropped to a level at which it was more efficient to re-inject electrons into the ring rather than continue data acquisition.

4 Beam monitor

4.1 Motivation

There will be a need to measure the ‘shape’ of the gamma ray beam at HIGS. The proposed detector will provide information about the intensity of the beam spot in two dimensions. This will help ensure that the beam is not drifting over time and remains properly centered on the target of interest. Also, the monitor may help identify any irregularities in the beam, such as if it is being clipped in some manner.

4.2 Overview

The proposed detector was an 'L' shaped piece of NE102 that was to sweep across the beam at a 45 degree angle to the horizontal. The project was to determine if a detector of this design was feasible and, if so, what the optimal dimensions would be for it. Several factors needed to be considered, including the maximum count rate in the detector, the minimum total number of counts, the scan time, and the resolution and accuracy of the detector.

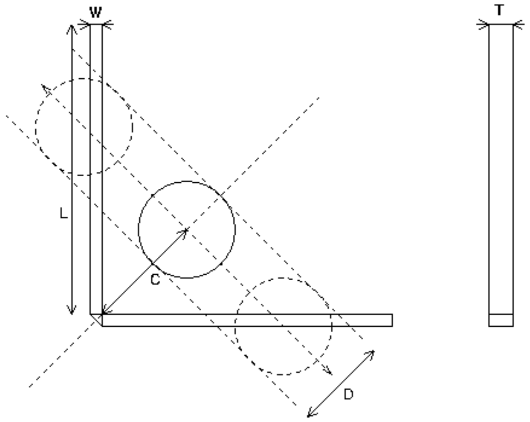


Figure 1: Basic set-up of the detector. What is referred to in this report as the detector thickness is labelled T on the diagram, and what is referred to as the width is labelled W. The detector arm length is labelled L and the beam centerline placement is labelled C. The diameter of the beam spot is D.

To ensure that the detector had optimal dimensions, the effects of changing several variables were studied. The effects due to the beam spot distribution, flux, and energy, the addition of other beam elements, and the addition of a converter were all studied, as were the effects of changing the detector's dimensions.

4.3 Technique/Procedure

GEANT software was used to simulate the detector and other beam elements (as necessary), and determine the effects of any changes made in the detector dimensions or initial conditions of the simulation.

The detector was moved to different positions from within GEANT to simulate it sweeping across the beam. To accomplish this, different geometry files were written for each detector position and simply called from GEANT's command prompt. As each different geometry file was called, a certain number of photons were triggered, corresponding to the number of photons that would pass by the detector in the amount of time that the detector would spend in each position for a certain flux.

The scan time for all simulations was kept at about one minute. One of the conditions given for the detector is that it must be able to complete its scan in about one minute, with at least 10,000 counts in the scan. By keeping the scans at their maximum allowable time, we can ensure that the proposed detector will meet the minimum count requirement for all situations. It may be possible at higher fluxes to decrease the scan time, and still reach the minimum count requirement.

A photon was determined to have been 'detected' if it deposited a certain minimum energy within the NE102. A record was kept of the number of photons (or other particles) detected in each detector position, and plotted to give intensity graphs in both the x and y directions. This was compared to the graphs of the known intensity in the x and y directions of the photon beam using the chi-squared test.

Several different beam spots were tested to ensure that the detector was accurate in a variety of situations. The detectors were tested with uniform intensity beam spots, Gaussian distributions, and distributions with two small Gaussians. As well, the energies were varied between 2 MeV and 50 MeV.

The other beam elements added were an aluminum outrun window, an iron collimator, and an aluminum pre-collimator, as seen in Figure 2. The aluminum outrun window was 0.5 mm thick, and 8.0 cm by 8.0 cm on the face. The precollimator was an inch thick cylinder, with an inside diameter of 2.5 inches and an outside diameter of 5 inches. The collimator was a cube, 4.0 inches per side, with a 1 inch inner diameter. The amount of space between the beam elements is given on Figure 2.

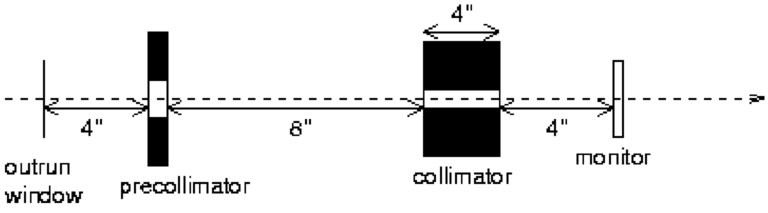


Figure 2: Other beam elements.

The detector was also tested briefly in a position upstream of the collimator. It was placed four inches downstream of the precollimator.

4.4 Data/Observations

4.4.1 Thickness of the Detector

The thickness of the detector affected both the total number of counts in a scan and the detector's count rate. As the detector became thicker, more photons were converted within the detector. This caused increases in the total number of counts, and thus the count rates.

Table 1 gives a comparison of the maximum rates reached in several different beam spots. These rates are listed in MHz, for a 1 GHz gamma ray beam flux (estimated from 1 MHz simulations). In each case, the detector's face remains the same size (10.414 cm by 0.254 cm), and only the thickness of the detector changes. These simulations were of the detector in vacuum, with no other beam elements present.

Table 1: The effects of detector thickness on the maximum count rate in the detector, at 1 GHz beam flux for several different beam spots. All rates are listed in MHz.

Beam Spot Distribution	Detector Thickness (cm)			
	0.075	0.45	0.75	1.70
Gaussian, sigma = 1 cm	0.18	1.01	1.64	3.65
Uniform, radius = 2.54 cm	0.12	0.63	1.03	2.33
Two Gaussians, sigma = 0.2 cm	0.64	3.79	6.24	14.09

Table 2 gives a comparison of the total counts reached in the same beam spots, except at a much lower flux (10 kHz). The numbers given are for the half of the scan the covers the horizontal profile. As before, the detector's face remains the same size (10.414 cm by 0.254 cm), and only the thickness changes. These results are also for the detector in vacuum with no other beam elements present.

Table 2: The effects of detector thickness on the total counts in a scan, at 10 kHz beam flux.

Beam Spot Distribution	Detector Thickness (cm)			
	0.075	0.45	0.75	1.70
Gaussian, sigma = 1 cm	29	152	260	548
Uniform, radius = 2.54 cm	21	142	254	562
Two Gaussians, sigma = 0.2 cm	21	126	209	516

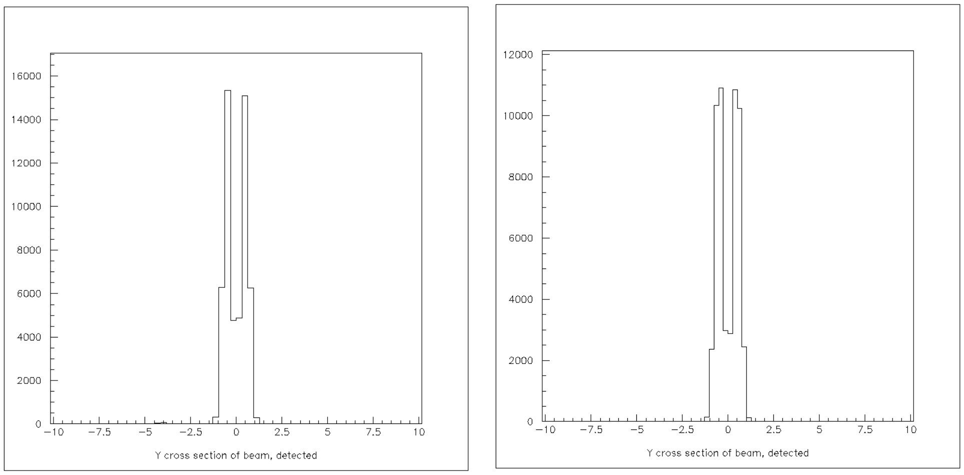
At a 1 MHz beam flux, these numbers become closer to the number required in order to get a sufficiently accurate beam scan. Table 3 compares the number of counts reached in the horizontal profile of each of the beam spots listed above, at 1MHz.

Table 3: The effects of detector thickness on the total counts in a scan, at 1 MHz beam flux.

Beam Spot Distribution	Detector Thickness (cm)			
	0.075	0.45	0.75	1.70
Gaussian, sigma = 1 cm	2439	14264	23816	53235
Uniform, radius = 2.54 cm	2435	14234	23809	53220
Two Gaussians, sigma = 0.2 cm	2420	14232	23563	53075

4.4.2 Width of the Detector

The width of the detector mainly affected the resolution of the beam scan. As can be seen in Figure 3, thinner detectors have slightly better spatial resolution.



(a) *(b)*

Figure 3: The effects of changing the width of the detector on the resolution of the beam scan. In (a), we see the results of a scan in which a wider detector (1/8”) was used, and in (b), a thinner one (1/10”). Note: The detector used in (a) was also somewhat thicker, accounting for its higher total count.

4.4.3 Length of the Detector Arms

The length of the detector arms affected the ability of the detector to determine the total background. Once other beam elements were added in the simulations, the beam would cause some ‘spray’ when interacting with these elements.

The longer arms allowed a greater beam centerline placement, as seen in Figure 4.

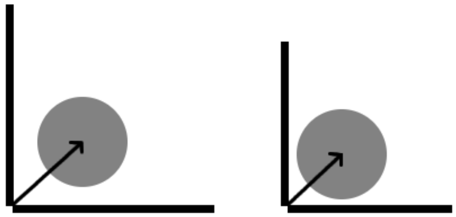
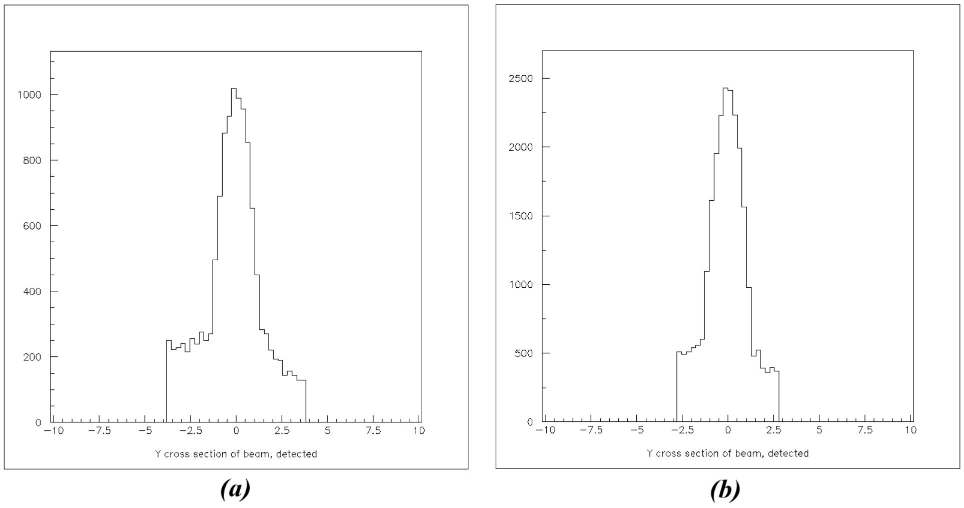


Figure 4: The detector on the left, with longer arms, allows for more space between it and the beam spot in its central position.

Because the detector had more time in the middle of the scan in which it was not interacting with the beam, it allows more measurements of the background. As can be seen in Figure 5, this allows us to make a better determination of the background rate.



(a) *(b)*

Figure 5: In (a), we have more measurements of the background than in (b), which allows us to determine the background more accurately. Note: these detectors had slightly different thicknesses, accounting for the higher count rate in (b).

4.4.4 Effects of Other Beam Elements

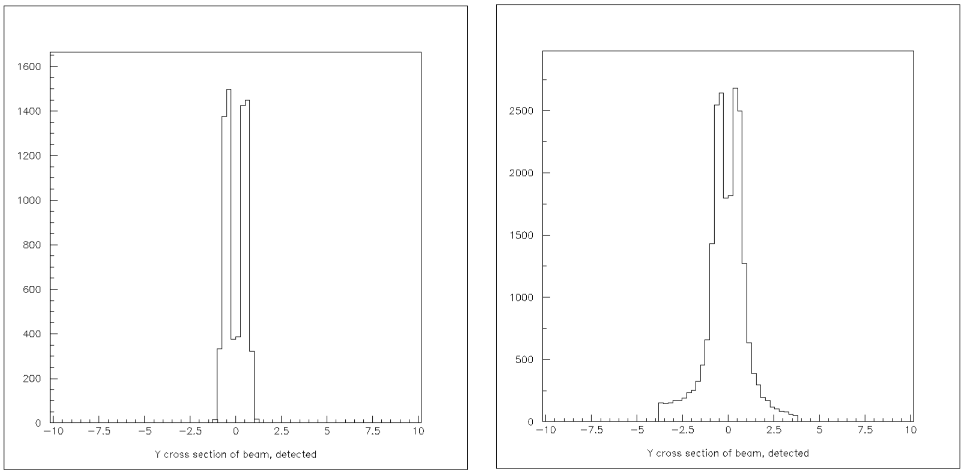
As previously mentioned, the other beam elements create a “background”, on top of which the beam spot sits. In general, when a greater amount of the beam interacts with the collimator, there is a greater amount of background seen from the collimator. When the beam spot does not interact with the collimator, the greatest amount of background seen is from the outrun window, and it is significantly decreased by the collimator. Air produced a very small amount of background (geenrally about 3% of the peak counts).

The amount of background seen can vary quite a bit. In instances where a significant portion of the beam interacts with the collimator, the number of counts per bin in the background can be up to half of the maximum number of counts in the peak of the beam. This applies to the detector in both the upstream and downstream positions from the collimator. In instances where the beam does not interact with the collimator greatly, there is very little background. However, it is still preferable to have the monitor in the downstream position, as the collimator blocks most of the background from the outrun window.

4.4.5 Effects of a Converter

Several different types of converters were tested. It was found that a 3.0 mm lead ‘L’ shaped converter had the best conversion rates; however, due to the malleability of lead, it was decided that a converter this small would be difficult to maintain in good condition. The next best conversion rates came from a 5.0 mm iron ‘L’ shaped converter. This increased the total number of counts in a scan by a factor of about six (at 10 MeV).

A plate converter was briefly tested, but it ‘smears’ the beam spot too greatly to be of practical use. As seen in Figure 6, an ‘L’ shaped converter of the same thickness had much better resolution.



(a) *(b)*

Figure 6: Effects of plate and ‘L’ shaped converters. We can see in (b) how using the plate converter affects the resolution of the scan as compared with the ‘L’ shaped converter used in producing the graph in (a).

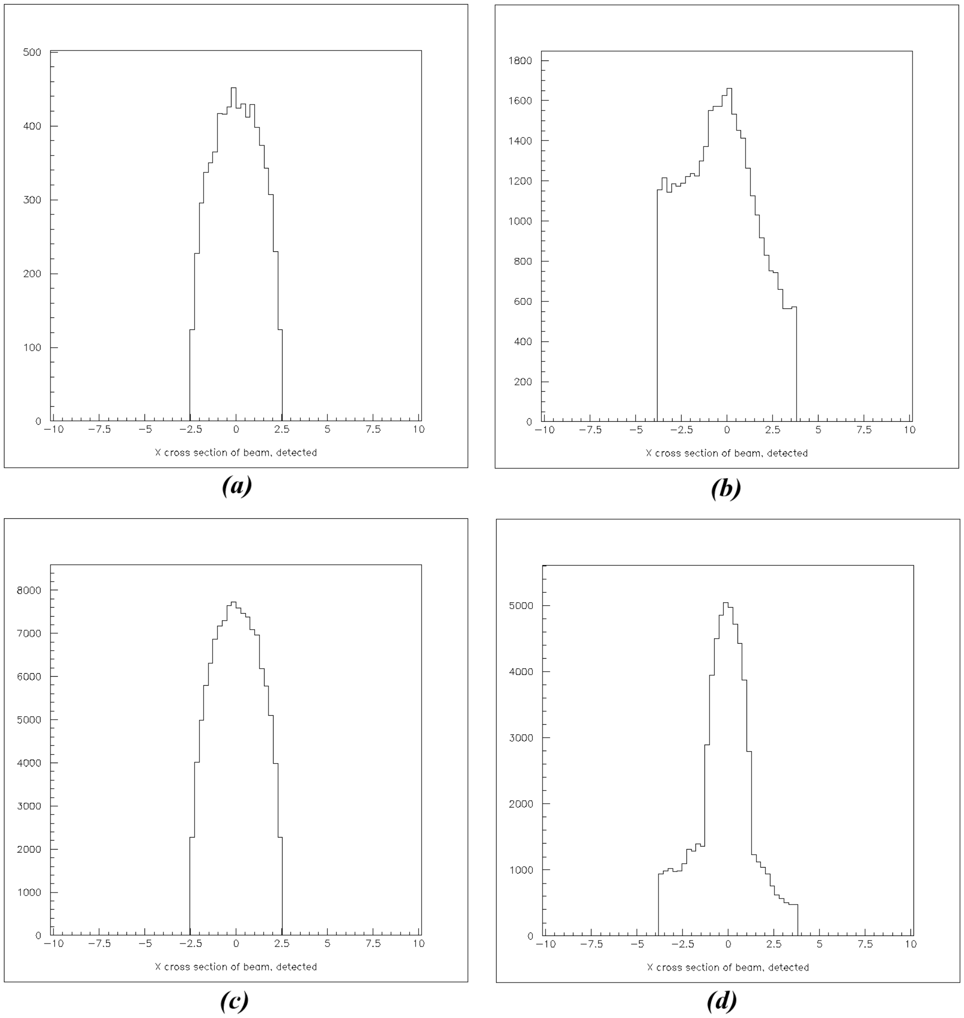
4.4.6 Movement of the Beam Spot

The movement of the beam spot has little effect on the number of counts detected (unless the beam spot intercepts the collimator to a greater degree). Movement of the beam spot is generally used to test the ability of the monitor to detect changes in the position of the beam spot.

The resolution of the detector was found to be about half the width of the detector. However, when dealing with smaller fluxes, the beam scan is not as accurate, and this creates some uncertainty in the resolution.

4.4.7 Different Beam Energies

When the converter is being tested in vacuum, the beam scans yield very different results than when the detector is being tested with all other beam elements present. In vacuum, the counts decrease with increasing energy if no converter is used, and increase with increasing energy if a converter is used. However, with all other beam elements present, the counts increase with increasing energy. This is due in large part to the increased amount of background generated within the collimator. So, for the larger energies (20 MeV or greater), there is a very large background. If a converter is present, much of this background is eliminated before it reaches the detector. However, if no converter is present, the background is large enough to almost completely hide the signal. Figure 7 gives a comparison of scans done in vacuum or with other beam elements present, with and without converters.



(a) *(b)*

(c) *(d)*

Figure 7: Effects of energy on beam spot detection. Here, (a) and (b) have no converters, while (c) and (d) have 0.50 cm iron 'L' shaped converters. The scans in (a) and (c) were produced in vacuum, with no other beam elements present, and (b) and (d) were produced with all other elements present. Note: the beam spot appears thinner due to collimation. All scans were produced using a 30 MeV gamma beam.

Table 4 shows the total number of counts in the x direction of the scan, for a 100 kHz scan.

Table 4: The effects of changing energy on the number of counts. Note that when all other beam elements are added, the beam spots listed here are collimated and therefore have smaller counts.

Beam Spot Distribution	Converter?	Beam Elements Present	Beam Energy (MeV)						
			2	5	10	20	30	40	50
Uniform, radius = 2.54 cm	No Converter	Vacuum	2181	1314	959	786	689	683	662
		All other elements	767	814	1150	2286	3500	4882	6355
	Converter	Vacuum	2818	3251	5918	10028	11917	12899	13649
		All other elements	911	1288	2492	4530	6120	7618	9447
Gaussian, sigma = 2.54 cm	No Converter	Vacuum	2242	1367	1012	808	753	717	693
		All other elements	904	878	1201	2209	3389	4855	6149
	Converter	Vacuum	2861	3536	6072	9974	11986	13070	13849
		All other elements	1084	1556	2738	5038	6782	8594	10179

4.5 Analysis

In order to determine the best design possible, it was necessary to examine the maximum count rate, the minimum total number of counts, and the resolution and accuracy of the detector.

Because of the physical limitations of electronics which will be used to determine the beam intensity, we must ensure that the detection count rate remains on the order of 10^5 Hz, for the upper beam flux (1 GHz) in which the detector will be used. The major factors affecting the count rates were the thickness of the detector and whether or not a converter was used.

Due to the statistical nature of data acquisition, we must ensure that at least 10,000 counts are in each beam scan. Again, the major factors affecting this are the thickness of the detector and whether or not a converter was used.

The accuracy of the detector was closely tied with the number of counts in a scan. When the number increased, more accurate scans were produced. So, we would like to keep the number of counts as high as possible without making the count rate too high.

The resolution of the detector was, in general, about half of the width of the detector. However, the resolution is also affected by the accuracy of the detector. Again, we would like to increase the number of counts in order to achieve better accuracy, and therefore better resolution.

4.6 Conclusions

This detector was found to be a feasible design. The optimal dimensions for each of the arms are a length of 11.176 cm, a width of 0.254 cm, and a thickness of 0.45 cm. An ‘L’ shaped converter, made of 0.50 cm thick iron, is also recommended.

The detector, by itself, will be work best over the 1 MHz to 1 GHz range. With the converter, it will cover the 100 kHz to 100 MHz range. It is preferable to operate with the converter, if possible, due to its effects on the amount of background detected.

5 Hardware Testing

5.1 Overview

There was a plastic scintillator which needed to be tested in its ability to determine a beam spot. The detector being tested was placed at different positions within a 'beam' produced by collimating a gamma source. The number of counts, which is directly related to the intensity of the 'beam', were determined in each different positions using a counter/timer module.

5.2 Technique/Procedure

The output from the phototube attached to the scintillator was put into a CFD, and the output of the CFD was run into a counter/timer. The threshold levels for the discriminator were determined using both sodium-22 and ruthenium sources.

The source was placed inside of a collimator tube, which was in turn placed within a collimator block. Several tests were made with the plastic detector centered on the collimator opening, to determine what would likely be the peak detection rate. Based upon this, the source was moved to a position which provided the best collimation, yet still had enough counts that a scan could be performed within a reasonable time span.

The detector and its phototube were secured upon a movable platform. The height from the bottom of the detector to the tabletop was measured, and the counter/timer unit was set to a 1000.0 s count time. Measurements were made at different detector positions to determine the shape of the 'beam'.

5.3 Data/Observations

In general, the 'beam' intensity was found to be higher near the center of the center of the beam. However, due to drifts in the electronics, some very high counts were produced at unreasonable positions. For example, one measurement at a position 5.5 cm below the center of the collimator opening was 3415 counts, whereas at the center of the opening only 2839 counts were recorded.

5.4 Conclusions

No definite conclusions were reached. If this measurement is to be repeated, it would be advisable to ensure that there is a reasonable method of monitoring the gains. This would allow the scaling of measurements which are above or below their expected values.