Position sensitive detection system for charged particles

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The position sensitive detection system presented in this work employs the Anger logic algorithm to determine the position of the light spark produced by the passage of charged particles on a $170 \times 170 \times 10$ mm^3 scintillator material (PILOT-U). The detection system consists of a matrix of nine photomultipliers, covering a fraction of the back area of the scintillators. Tests made with a non-collimated alpha particle source together with a Monte Carlo simulation that reproduces the data, suggest an intrinsic position resolution of up to 6 mm is achieved.

Keywords: Scintillating charge particle detector; position sensitive; Anger logic.

En este trabajo se presenta un detector centellador en el que se determina la posición del destello luminoso producido por el paso de partículas cargadas mediante la lógica Anger. El material sensible del detector es una placa centelladora (PILOT-U) de $170 \times 170 \times 10$ mm^3. La luz producida es recibida por un arreglo de nueve fotomultiplicadores acoplados a una de las caras de la placa. Los datos obtenidos utilizando una fuente radioactiva emisora alfa, en comparación con simulaciones Monte Carlo, sugieren una resolución intrínseca para la determinación de la posición de 6 mm para este sistema.

Descriptores: Detector centellador para partículas cargadas; sensible a la posición; lógica Anger.

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1. Introduction

Nuclear reaction cross section measurements often require the counting of reaction products emitted in a variety of angular directions. In binary reactions, the available solid angle can be explored by varying the position of a single detector in repeated measurements. This strategy is straightforward, requires very little electronics but is time consuming in the data taking process and the off line analysis.

Reliable modern measurement of angular distributions in nuclear reactions is best achieved by simultaneous detection of the reaction products over a large fraction of the relevant angular range. One approach often used is to employ a multi-detector array that covers a large solid angle. The position resolution is associated with the size of each individual detector element. This procedure requires the availability of a large number of electronic channels, which turns the experiment and the analysis complex, cumbersome and expensive.

The position sensitive detection system for charged particles presented in this work provides a flexible and low budget approach. It consists of a plastic scintillator slab viewed by an array of nine photomultipliers and employs the Anger logic algorithm, which weighs the intensity of the output signal from each photomultiplier by its relative position to determine the position of incident charged radiation.

In order to gain a better understanding of the response of the system, Monte Carlo simulations of the distribution of light following the passage of charged particles through the scintillator were performed with a FORTRAN code we developed for this purpose

This work is an extension to charged particle detectors from previous efforts from the group at UNAM in Mexico to develop position sensitive large neutron detectors (see [1, 2]).

2. Detection system

2.1. Scintillator

The detector of the system is a 170 x 170 x 10 mm^3 Pilot-U slab. Pilot-U is a commercial version of the EJ-228 plastic scintillator designed by Eljen Technology for very fast timing applications. Detailed information about this material can be found in [3] but for convenience, we reproduce here some of its properties in Table I.

TABLE I. Properties of the EJ-228 plastic scintillator.

Light output (relative to anthracene)	67.00%
Photons per MeV (for electrons)	10000
Wavelength of maximum emission	391 nm
Decay time	1.4 ns
Refractive index	1.58

2.2. Light guides

Our photomultipliers have a cylindrical μ-metal shielding, provided to work in environments where intense magnetic fields are present. In the region of the photocathode, the shielding extends 20 mm beyond its surface (see Figure 1). Because of that, the nine photomultipliers used in the array are coupled to the back face of the scintillator via individual acrylic light guides, as shown in Figure 1.

The refractive index of the light guides is 1.49, which yields a total internal reflection angle of 70.5 degrees. The angles chosen to machine the light guides were selected to ensure total transmission of light through the guide. Each of these light guides catches photons from a 50×50 mm^2 surface and transmits them to the photomultiplier's cathode, see figure 2.

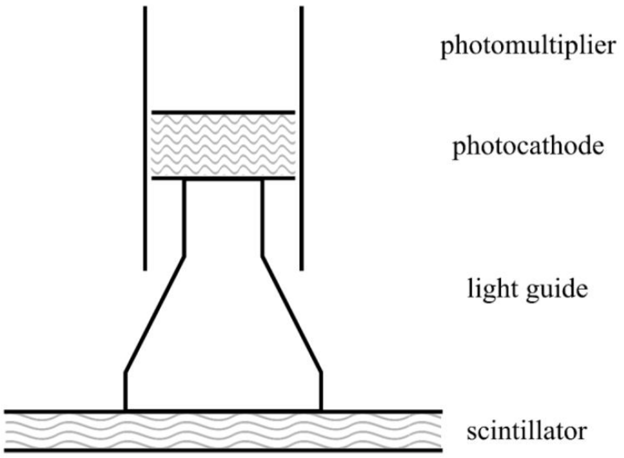

FIGURE 1. Schematic (not to scale) view of the coupling between each photomultiplier and the scintillator's back face, achieved through acrylic light guides. A thin layer of optic grease is used in the couplings.

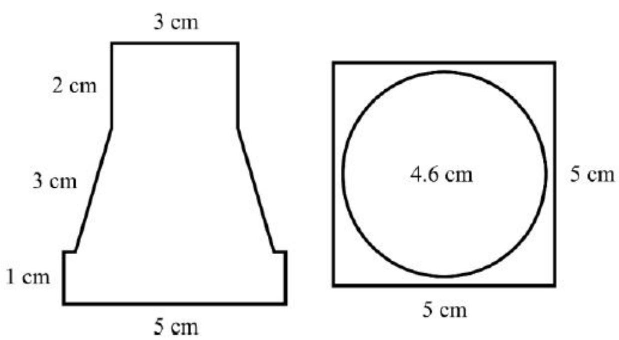

FIGURE 2. Schematic views of the light guides.

TABLE II. Properties of a RCA4523 photomultiplier tube.

Window's diameter	75 mm
Photocathode's diameter	51 mm
Wavelength of maximum response	450 nm
Quantum efficiency (at 400 nm)	22.00%
Refractive index	1.52

2.3. Photomultipliers

Some of the main characteristics of the RCA4523 photomultipliers are listed in table II [4].

Even though the wavelength of maximum response is close to the wavelength of maximum emission of the Pilot-U scintillator, quantum efficiency diminishes the output signal intensity. Figure 3 shows side and perspective views of the assembled detection system with the nine photomultipliers attached to the back of the scintillating slab through the acrylic light guides.

3. Position of an event

The position of an event of interest is determined by weighting the intensity of the output signal from each photomultiplier by its own position, according to the Anger logic algorithm [5-7]

$$r = \frac{\sum_i I_i r_i}{\sum_i I_i}. \tag{1}$$

In this expression r is the calculated position of the event over the XY plane (see Figure 3); r_i and I_i are the position and amplitude of the signal delivered by the i-th photomultiplier.

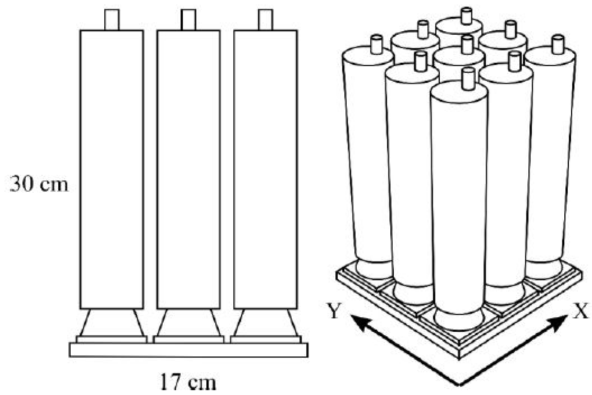

FIGURE 3. Front and perspective views of the detection system. The Cartesian coordinate system used by the Anger logic algorithm is also shown.

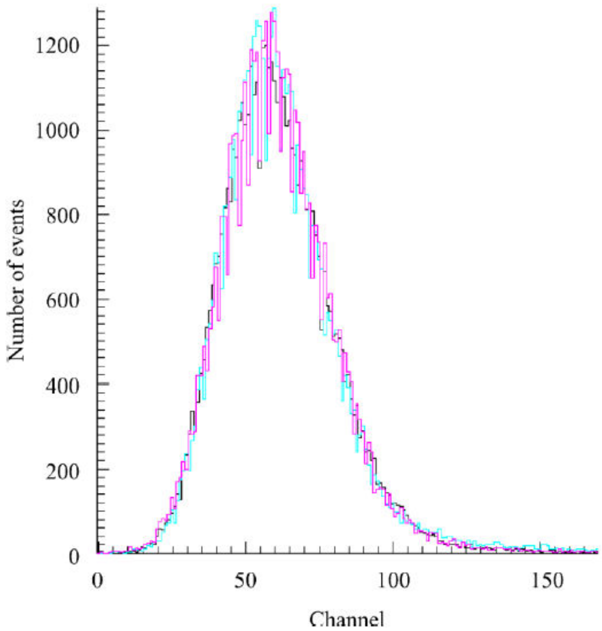

FIGURE 4. (Color in line) Pulse height distributions generated for three different photomultipliers when a triple alpha source was placed in front of them. Centroids and widths are perfectly matched.

A (CAMAC) multi-parametric acquisition system is triggered whenever at least one of the signals from the photomultipliers surpasses a previously established threshold, imposed by constant fraction discriminators. When an event triggers the acquisition system, the signals are integrated over 150 ns and digitized by a set of Charge to Digital Converters (QDC). Data is stored in the computer disc on an event by event mode for off-line analysis.

It is important to clarify some points about the algorithm we are working with, and the processing of the signals:

- The position of each event is established on a two-dimensional basis, *i.e.*, for each event, the Anger logic algorithm calculates the value of their coordinates over a plane parallel to the scintillator's front face. This approach is good enough for low energy alpha particles (like the ones employed in our tests) and higher energy heavy ions ($E > 10$ MeV/A), since they all stop within a thin layer (a few microns) next to the front face of the scintillator.

- Additional treatment to derive the coordinates of the position might be needed for longer tracks, produced for instances by energetic light ions, instead of point sparks (our scintillator material is 1 cm thick, which is the range of 50 MeV protons). This problem is not treated in the present work.

- Because of the low number of photomultipliers used in this device, it cannot provide separate positions from two or more simultaneous hits. Events with more than one hit, can be identified since they produce incoherent information if assumed a single hit.

In what concerns our algorithmic determination, the position of each photomultiplier is taken to be the center of the light guide attached to it. In order to implement it, all photomultipliers must have the same gain. Figure 4 shows an example of the gain match achieved with data from several photomultipliers after fine tuning the operational voltage on each tube, including a software calibration.

4. System performance

The detection system performance was tested with a triple alpha source (^{239}Pu, ^{241}Am and ^{244}Cm). This is an electrodeposited source on a disc with an active circular spot of 3 mm diameter. In these experiments, the source was placed in different known positions in front of the detector at a constant distance of 3 mm from it without collimation. The alpha particles travel through air before they reach the scintillator. With this geometry alpha particles of at least 1.5 MeV illuminate a circle of 30 mm diameter in the front face of the detector. Because of the different path lengths of the alpha particles in air, the energy loss is variable and the energy spectrum becomes broad.

The position of each event was determined employing the Anger logic algorithm, as discussed above. Plotting counts as a function of X and Y coordinates generates histograms whose centroids are related to the source known position. The widths of the deduced positions are related to the intrinsic position resolution and the size of the source. The software employed for data analysis was *damm*, developed by Oak Ridge National Laboratory (ORNL). In Figure 5, two dimensional histograms show the calculated position of alpha hits for different runs, where the source was placed at different locations.

The one dimensional projections of the generated X and Y histograms have a full width at half maximum (FWHM) below 14 mm and their centroids are plotted in Figure 6 as a function of the known coordinates of the source X' and Y', respectively. It is worth noticing that there are differences between both quantities. These differences can be attributed mainly to the fact that a significant fraction of the light produced in every event is not collected. The curve in figure 6 becomes a calibration function to convert the position obtained directly with the Anger algorithm to real positions.

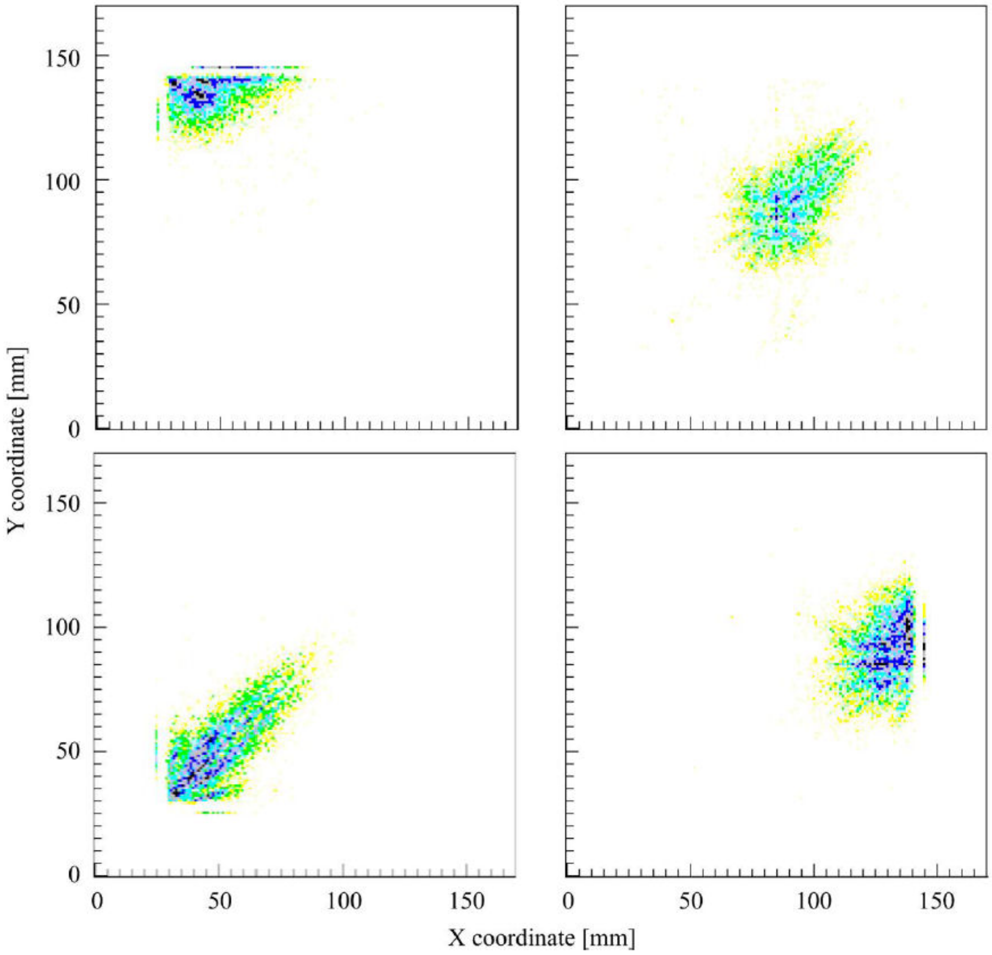

FIGURE 5. (Color in line) Two-dimensional X-Y histograms from four data runs. The coordinates on the XY plane of the alpha source were: Upper left (25, 145), upper right (85, 85), lower left (25, 25), lower right (145, 85).

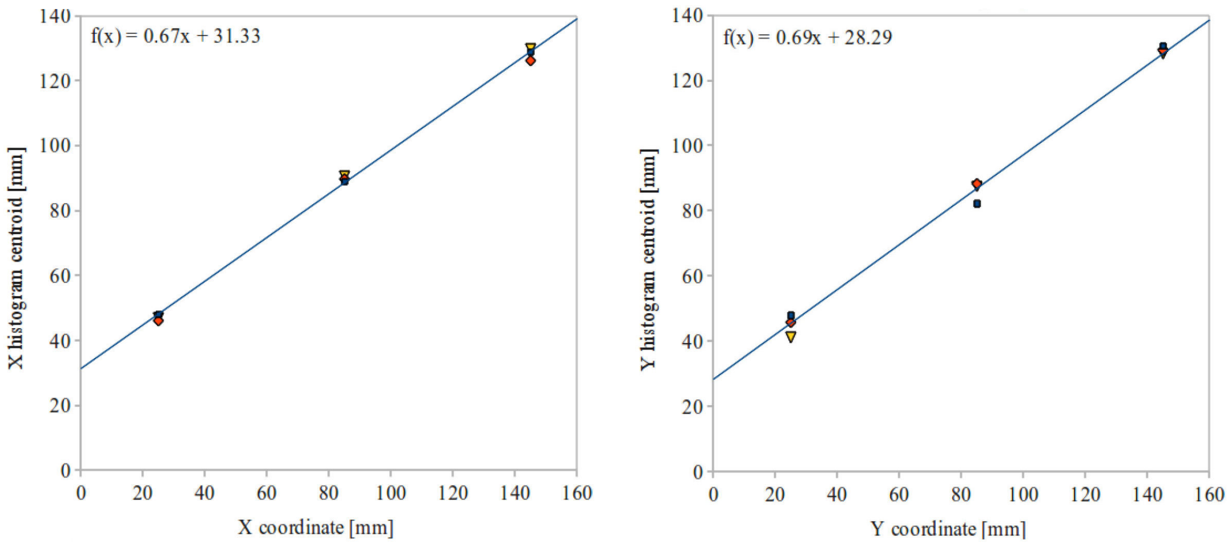

FIGURE 6. (Color in line) Centroids of the X and Y histograms as functions of known X and Y coordinates of the source, respectively. A linear fit calibrates the system.

Because of the very limited number of points available a linear fit is enough to produce our calibration functions. These functions are

$$X' = \frac{X - 30.78 \text{ mm}}{0.68},$$
$$Y' = \frac{Y - 26.9 \text{ mm}}{0.70}. \quad (2)$$

5. Monte Carlo simulations

A better understanding of the detection system, and the different factors contributing to its resolving power, can be achieved by comparing the measured data to simulated data under similar conditions. The simulation programmed developed for this purpose generates, randomly or not, the position where a charged particle enters the detector. From this point a number of photons proportional to the deposited energy, are emitted with an isotropic distribution in all directions. Each photon is followed through the scintillator; and, every time a photon reaches the back face of the scintillator within the surface of a light guide's base it is assumed to be detected by the corresponding photomultiplier. Assuming that the intensity of the output signal of a photomultiplier is proportional to the number of photons that reach it, it is possible to apply Anger logic to the counters to determine the position of the source of the photons in the simulation.

The simulation was adjusted to reproduce the experimental data obtained with the alpha source. Two dimensional X-Y histograms as well as their projections were generated to compare to real data.

From the results shown in figures 7 and 8, we concluded that the program actually simulates fairly well real data.

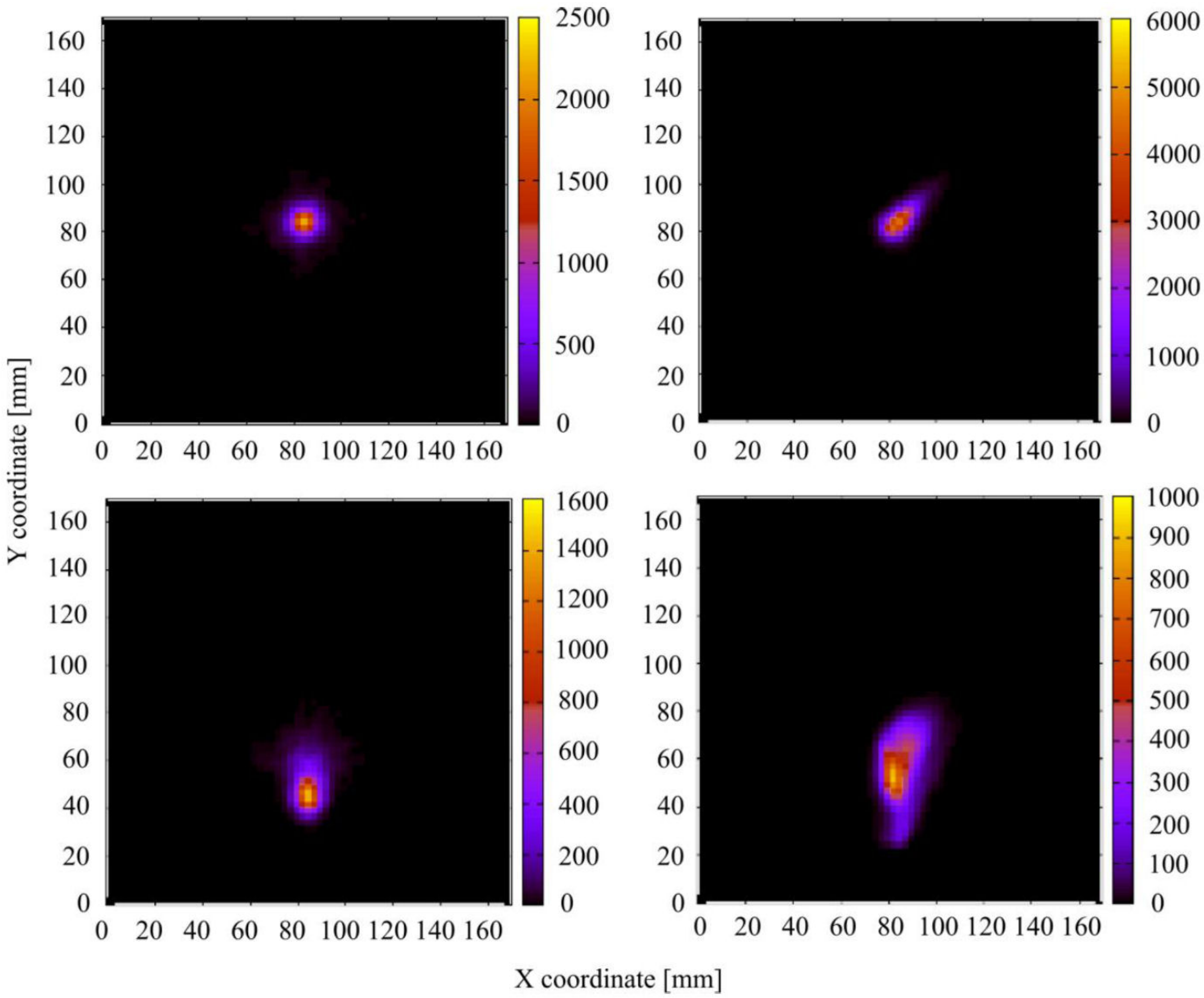

FIGURE 7. (Color in line) On the left, a pair of simulated three-dimensional histograms are shown. The coordinates of the source were: Up (85, 85), down (85, 25). On the right, the real (experimental) counterparts of the simulated histograms are shown.

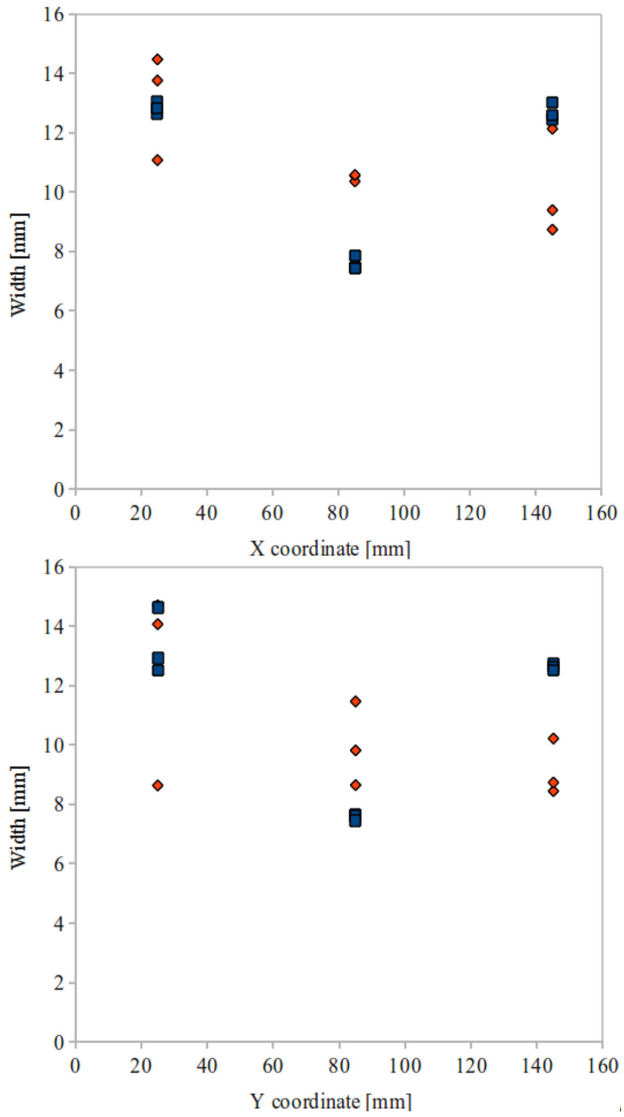

FIGURE 8. (Color in line) Widths of the X and Y histograms as functions of known X and Y coordinates of the source, respectively. Blue squares and orange diamonds represent simulated and real data, respectively.

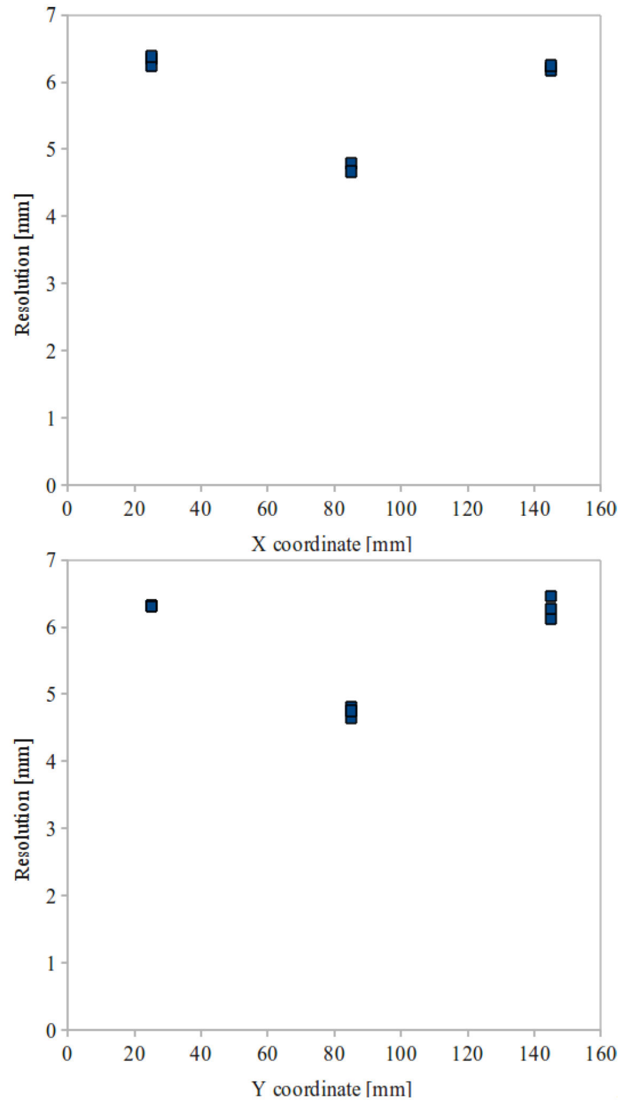

FIGURE 9. (Color in line) Widths of the X and Y histograms as functions of known X' and Y' coordinates of the point source. These values are suggested as the position resolution of the system.

This agreement allowed us to perform simulations assuming a point alpha particle source (collimated), with the purpose of deducing the intrinsic position resolution of the detection system. In figure 9, the centroids of the X and Y histograms for these tests are plotted as functions of known X' and Y' coordinates of the alpha beam.

As shown in the figure, the intrinsic position resolution is identical in both axis (as expected due to symmetry) and below 7 mm.

Once this detector is placed in a real experimental situation, inside a vacuum chamber at 200 mm from a point where nuclear reaction products are being generated, this position resolution of 7 mm translates into an angular resolution of better than 2 deg. Providing, at the same time, a large solid angle coverage, with a maximum detected angle of 117 degrees (polar).

Also, tests showed that the Anger logic algorithm can estimate the position of events outside the square region defined by the centers of the outer photomultipliers. A non linear fit needs to be proposed to achieve this, as shown in figure 10.

6. Conclusions

To detect charged particles produced in nuclear reactions, we often require a detection system which would cover a large solid angle when placed inside a reaction chamber. In this work we described one such detector with position resolution similar to that obtained with a large number of closely packed small units, yet, using far less electronic channels.

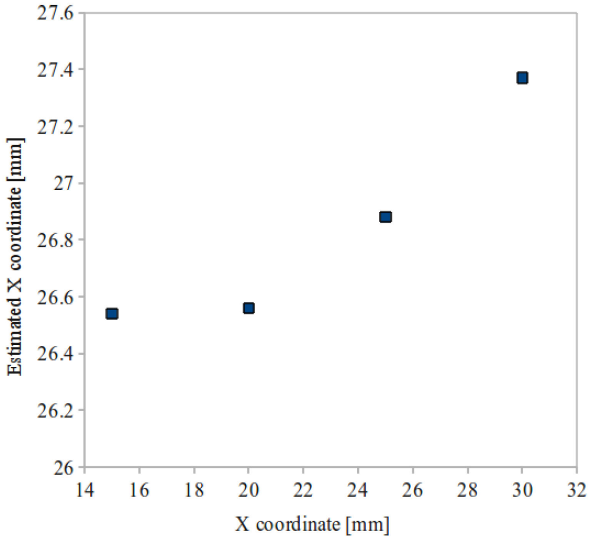

FIGURE 10. Employing the Anger logic algorithm to calculate the position of events outside the region delimited by the photodetectors' centers do not suffice. A non-linear fit is required in order to obtain the real position of the event.

The detection system designed, built and tested as shown in this work, consists of only nine electronic channels (nine photomultipliers, preamplifiers, digital converters, etcetera) in a symmetric 3×3 array, covering a sensitive area of $170 \times 170 \times 10$ mm^3, made of a square plate of plasticscintillating material thick enough to stop 50 MeV protons. In this case, we were interested only in the position resolution over the plane of incidence.

Our data analysis based on a modified Anger logic, together with a Monte Carlo simulation showed that the position where a particle hits the detector can be deduced to better than $\pm$ 7 mm with this simple array. To obtain the same position resolution with a segmented detector, it would require at least a 12 by 12 array of 14 mm squared elements or pixels, which would demand 144 electronic channels.

This detection system is easy to set, data is easy to analyze and its cost is greatly reduced relative to the segmented option.

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