OPTIMIZATION OF THE REFLECTOR DESIGN IN A LIQUID SCINTILLATION COUNTER WITH ONE PHOTODETECTOR

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ABSTRACT. Optics is a key issue in the design of liquid scintillation (LS) counters, and an adequate reflector configuration helps to improve light collection, which contributes to enhanced energy resolution and to the efficiency of these systems. This paper describes the calculations made in the study of LS counters with 1 hybrid photomultiplier tube (PMT) to be used in the measurement of alpha emitters. Various configurations of spherical reflectors, reflecting materials, and standard vials have been simulated with a computer program. The results are presented in terms of light collection efficiency as a function of these parameters. They allow for determination of the optimal setup for collecting the light in the photocathode area. Measurements made with diffuse spherical reflectors indicate that diffuse reflection results in an uniform light distribution all over the photocathode area, for which a spatial response is also characterized.

INTRODUCTION

Liquid scintillation counting (LSC) systems are based on the detection of light emitted as a result of the interaction between a radioactive sample and a scintillation cocktail. Photon detectors (photomultiplier tubes, hybrid photomultiplier tubes, diodes, and others) are used to measure the light emitted; therefore, optics plays an important role in the design of LSC systems. Most systems have 2 photon detectors working in coincidence mode, but models with a single detector are used to measure alpha emitters (McKlveen and McDowell 1976), and models with 3 detectors are used for absolute measurement of the activity contained in a vial (Pochwalski et al. 1988).

Reflector configuration is a major factor in the design of efficient instruments. For a given scintillation cocktail, a more efficient reflector will provide better energy resolution and counting efficiency. Reflector design must take into account the physical dimensions of the vials and the number of detectors. This paper focuses on the design of spherical reflectors for systems with a single hybrid photomultiplier tube (PMT) detector using standard scintillation vials for the measurement of alpha emitters.

CALCULATIONS

Background

Previous studies of LS counters with a single PMT have been published by Hanschke (1972), who studied 2 geometrical models of alpha-spectroscopy systems, and by McKlveen and McDowell (1976), who set up the basis for the design of these devices and extensively discussed their optical aspects. Later, Thorngate and Christian (1977) also studied several reflector geometries for this specific type of detector. These studies show that in order to collect the highest fraction of light, the reflector should be designed to take into account the following conditions:

- The number of reflections should be as small as possible;
- The reflections should not direct light rays to any obstacles where they can be absorbed or diverted from their way to the photocathode; and
- The reflecting material should have high reflectivity to minimize absorption in the walls.

We also show that spherical geometries are the most adequate for these purposes.

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LSC 2005, Advances in Liquid Scintillation Spectrometry
Edited by Stanisław Chałupnik, Franz Schönhofer, John Noakes. Pages 31–40.

Numerical Simulations

Several reflector configurations were tested using the computer program LucidShape (Brandenburg GMBH), which is based on Monte Carlo simulation. This program allows for the description of 3D systems, including optical components and light sources, together with their optical characteristics and geometry. The program also includes a fast algorithm for ray tracing.

The simulated reflector configurations are shown in Figures 1 and 2. They were selected in order to reach an agreement between the recommendations given in the literature (McKlveen and McDowell 1976; Thorngate and Christian 1977; Malcolm and Stanley 1976, 1977a,b) and the materials available. Both configurations present a spherical geometry with a circular window for the photocathode, but they differ in the relative position of vial and photodetector.

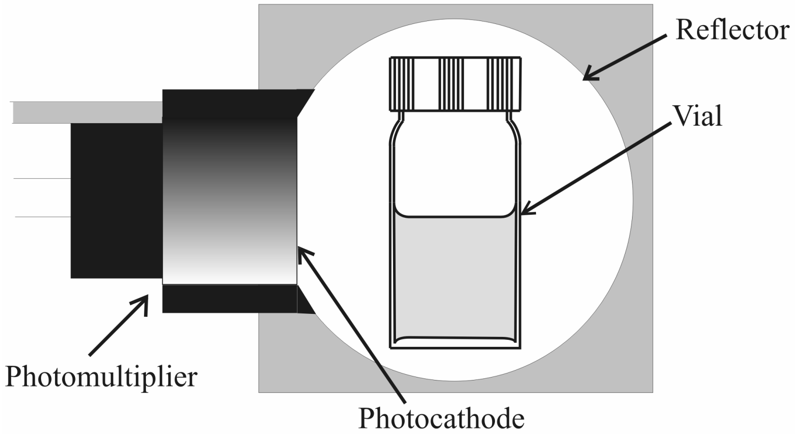

Figure 1 Scheme of configuration 1. A scintillation vial is situated inside a spherical reflector and a PMT with the photocathode surface parallel to the vertical axis of the vial.

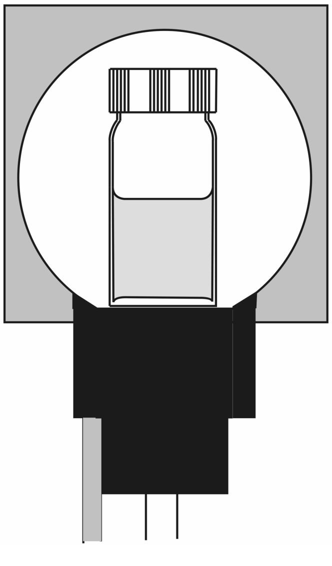

Figure 2 Scheme of configuration 2. Same elements as in configuration 1, but the vial is placed on the photocathode in direct contact with its surface.

The photocathode was described as a perfectly absorbent surface, homogeneous all over its area. Table 1 presents the main characteristics of the simulated setups.

Table 1 Parameters tested in the setups simulated in this work.

	Configuration 1	Configuration 2
Type of vial	20-mL borosilicate glass vial 8-mL borosilicate glass vial 20-mL polyethylene vial	
Reflector chamber radius	35, 37, 39, 41, 43, 45 mm	37.5 mm
Vial position	Varying along horizontal and vertical axes of the sphere	Vial bottom in contact with photocathode surface
Type of reflecting material	Diffuse and specular	

Three types of standard vials commonly used in LSC were considered, and their light emissions were modeled according to the characteristics corresponding to the different vial materials (Durán and García-Toraño 2005). In the polyethylene vial, the whole volume of the liquid was considered as a homogeneous light emitter, while in glass vials a region of higher emission intensity was set at the zone were the liquid meniscus is located. Two types of reflecting material, diffuse and specular, were used to model the reflector surface.

In configuration 1, the reflector radius was changed as indicated in Table 1, and the position of the vial along the vertical and horizontal axes of the sphere were also varied, thus changing the global geometry of the system. In configuration 2, the radius and position of the vial were not changed. In this setup, the vial is in direct contact with the photocathode surface, and the radius was kept constant with a value of 37.5 mm.

Results for Configuration 1

Figure 3 shows an example of the model created with LucidShape for configuration 1 together with its ray tracing. The configuration includes a 20-mL glass vial. Vials are described in great detail in the simulations and include the internal reflecting layer of the cap.

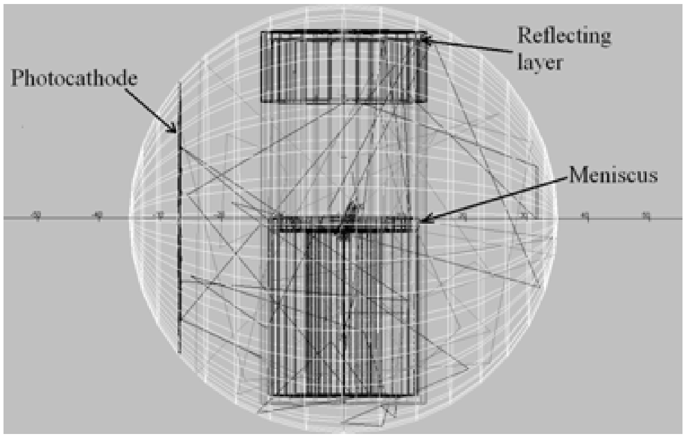

Figure 3 LucidShape model and ray tracing for configuration 1 with a 20-mL glass vial and 35-mm reflector radius. The meniscus region exhibits higher light emission intensity, following the experimental data (Durán and García-Toraño 2005).

Figures 4 to 6 correspond to the results obtained in the simulations. They show light collection efficiency as a function of vial types, reflecting material, reflector radius, and position of the vial along the horizontal and vertical axes of the sphere in terms of the distance to the photocathode and vertical displacement from the center of the sphere, respectively. Optimal values for each configuration are presented in Table 2. They are expressed as the ratio of light reaching the photocathode to the total light emitted by the vial.

Table 2 Optimal values of the percentage of light collected for configuration 1 (with a 35-mm radius) and configuration 2 with diffuse and specular reflectors and several types of vials.

	Percentage of light collected			
	Configuration 1		Configuration 2	
	Diffuse reflector	Specular reflector	Diffuse reflector	Specular reflector
20-mL glass vial	60.8%	39.6%	58.1%	37.6%
8-mL glass vial	72.1%	42.2%	70.2%	37.2%
20-mL polyethylene vial	58.8%	32.0%	59.1%	37.1%

In Figure 4, one can see that for spherical reflectors, a smaller radius leads to more efficient light collection. This can be explained by the fact that vials are closer to the photocathode, which results in a greater part of the emitted light reaching the photocathode directly, thus increasing the fraction of collected light.

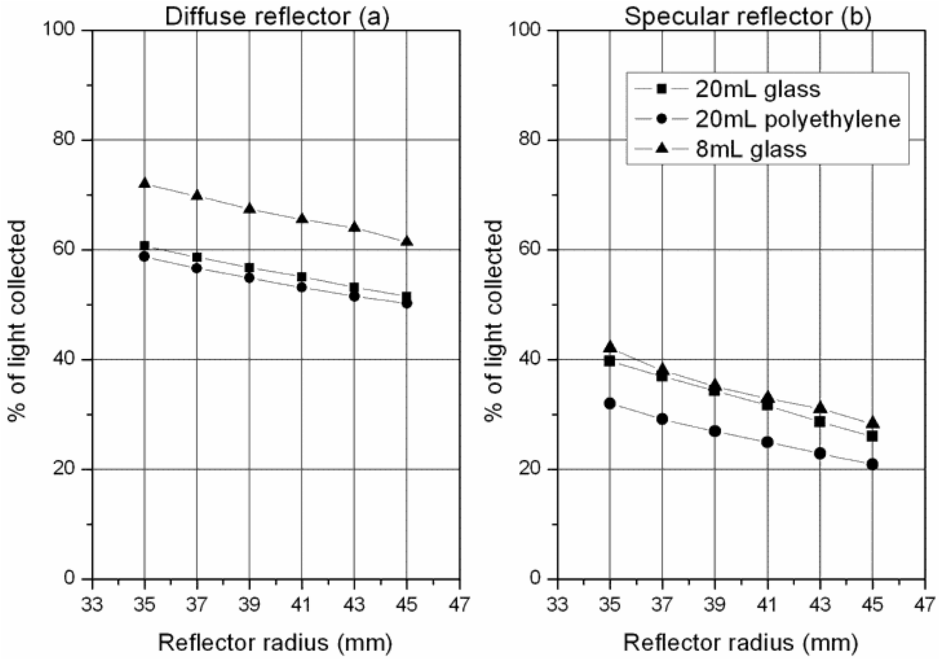

Figure 4 Light collection efficiency for configuration 1 for (a) diffuse and (b) specular reflector chambers as a function of its radius for several types of vials placed in the reflector center.

Figure 5 presents the variation of light collection efficiency as a function of the position of the vial along the horizontal axis in terms of the distance from the vial to the photocathode. For the diffuse reflector (Figure 5a), smaller distances lead to higher efficiencies. For the specular reflector (Figure 5b), collection efficiency increases with vial eccentricity. When the vial is located at the center of the sphere, photons have a high probability of being reflected back by the specular coating to the center of the sphere where the vial is placed. Here, they can be either absorbed or reflected, thus increasing the loss of light.

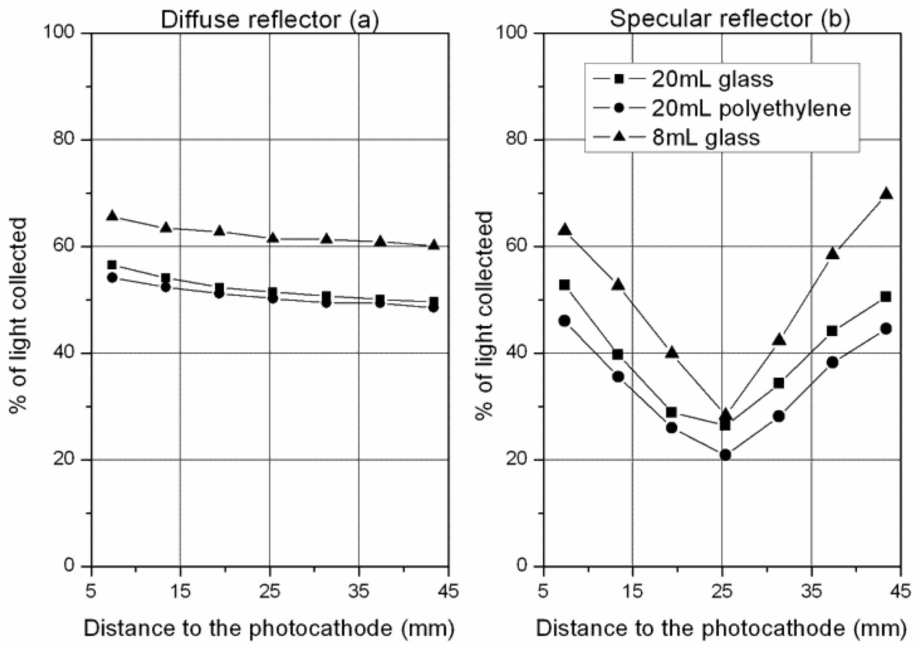

Figure 5 Light collection efficiency for configuration 1 for (a) diffuse and (b) specular reflector chambers with 45-mm radii as a function of the distance between the vial and the photocathode surface for several types of vials.

In Figure 6, one can see that the position of the vial along the vertical axis inside the reflector does not significantly affect light collection. If we admit the uniformity of the photocathode response, as is modeled in the simulations, the detection efficiency should not be influenced by the vertical position of the vial. If photocathodes present regions of different behavior and if the detection efficiency is not uniform all over the area, the alignment of the meniscus zone with the center of the photocathode is consistent with recommendations in the literature.

Another result that can be drawn from these data is that diffuse reflectors present a much more appropriate response than specular ones. The percentages of light collected are greater and are not significantly affected by the position of the vial. Diffuse reflectors obey Lambert's law with an isotropic distribution of reflected light, as they present an irregular surface where light can be reflected in any direction. On the other hand, specular reflectors reflect light with an angle that is equal to the incidence angle.

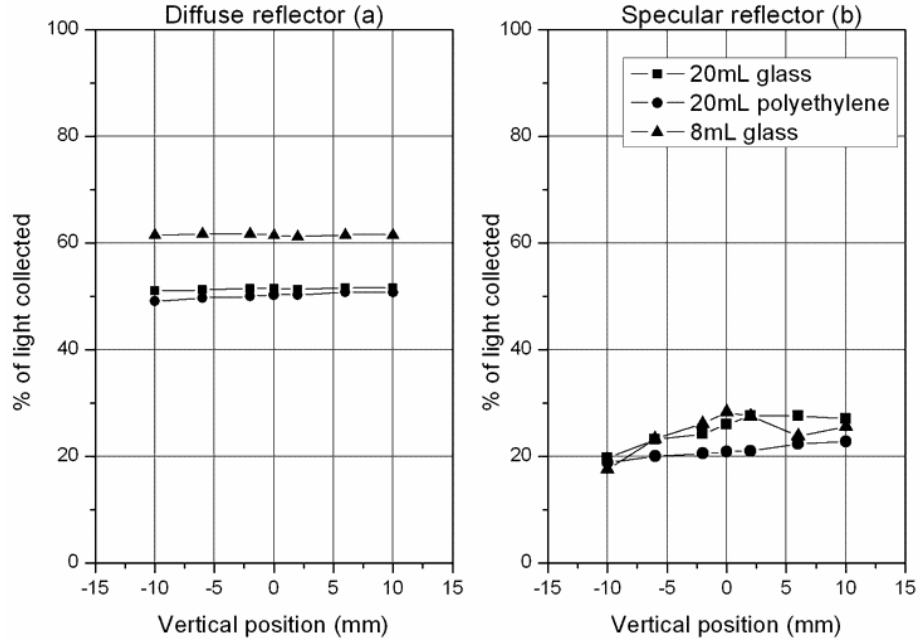

Figure 6 Light collection efficiency for configuration 1 for (a) diffuse and (b) specular reflector chambers with 45-mm radii as a function of the position of the vial along the vertical axis, measured as its displacement from the center, for several types of vials.

Results for Configuration 2

In configuration 2 (Figure 2), the vial is placed inside a spherical reflector chamber (37.5-mm radius) on top of the photocathode window directly on the center of its surface. Figure 7 presents a LucidShape graph for this configuration with a 20-mL polyethylene vial. Optimal values of light collection efficiency as a function of vial and reflector characteristics are presented in Table 2.

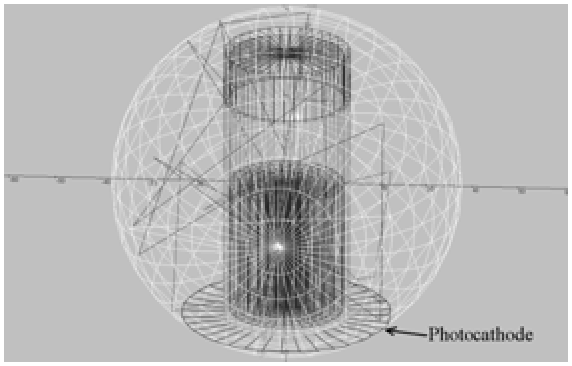

Figure 7 LucidShape model and ray tracing for configuration 2 with a 20-mL polyethylene vial and a 37.5-mm reflector radius. The position of the photocathode is indicated.

Comparison and Discussion

Numerical results obtained in the simulations of both configurations are summarized in Table 2. Data presented in the table correspond to the optimal values from each set. For configuration 1, the optimal value corresponds to the minimum reflector (35-mm radius) that can accommodate a standard vial. For configuration 2, the reflector radius was kept constant.

In general, better results are obtained with diffuse reflecting material and small differences are found between configuration 1 and configuration 2. In configuration 2 with a specular reflector, the result is not strongly dependent on the vial type, but light collection efficiency is significantly smaller. The best result from all tested conditions corresponds to an 8-mL glass minivial inside a diffuse reflector.

MEASUREMENTS

In the previous section, we show that diffuse reflectors are more effective in collecting light. A complete study of the measurement system, using a hybrid PMT (HPMT) as the photodetector, requires the additional description of 2 aspects: the spatial distribution of photons reaching the HPMT (not available from the simulations) and the uniformity in the response of the HPMT. This section describes the measurements made to characterize both aspects.

Light Distribution at the Photocathode Window

The experimental setup used for determining the spatial distribution of photons at the photocathode is shown in Figure 8.

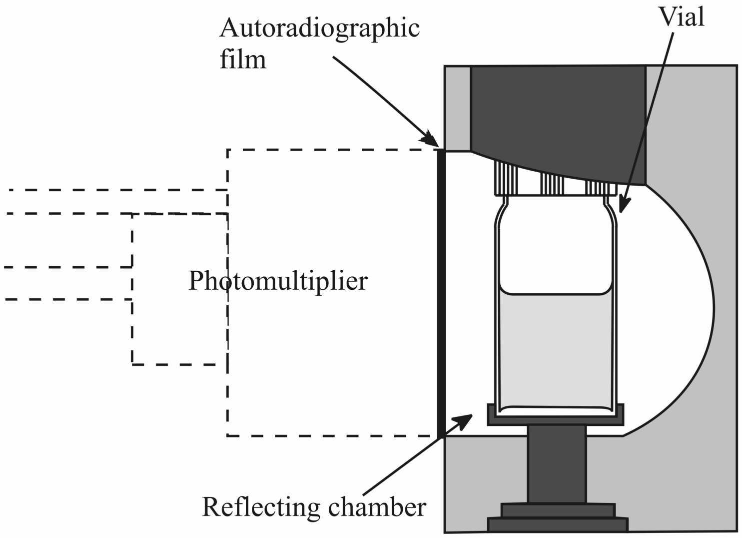

Figure 8 Experimental setup used to measure light distribution over the photocathode surface. The position of the autoradiographic film is indicated.

The reflector chamber has a pseudo-spherical shape and is coated with a diffuse reflecting paint (barium sulfate). A 20-mL glass vial filled with 15 mL of the scintillation cocktail HiSafe 3, containing 0.5 MBq of the beta-gamma emitter ^{131}I, was used as the light source. Autoradiographic film Kodak Biomax MS® was placed at the photocathode window to obtain an image of the light distribution arising there. The digitized image is presented in Figure 9, and optical density profiles along

2 perpendicular axes are shown in Figure 10. Results indicate that when diffuse reflectors are used, light is uniformly distributed all over the photocathode area.

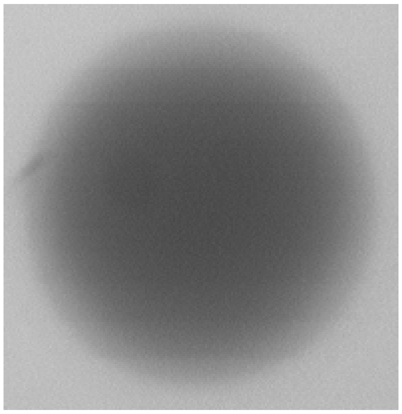

Figure 9 Autoradiograph taken in the photocathode window of a diffuse reflector chamber containing a 20-mL glass vial filled with a ^{131}I solution with 0.5 MBq for a 60-min exposure.

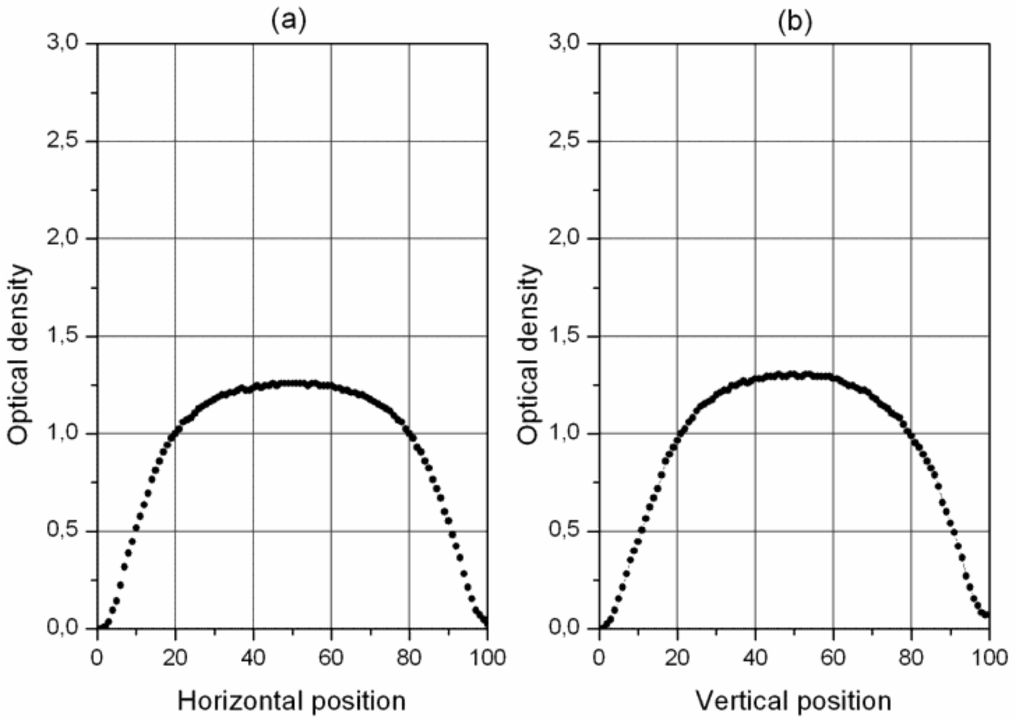

Figure 10 Optical density profile of Figure 9 along its (a) horizontal and (b) vertical axes

HPMT Response

The response of the HPMT (model PP0475B from DEP) was determined by a 2D scan of the photocathode surface using a UV LED. The light source was moved on a plane parallel to the photocathode surface with a 2-dimensional positioning stage. The photocathode is a 45-mm-diameter circular surface, and the grid size of the scan was set to 4 × 4 mm. Figure 11 shows the result of this measurement, where it can be appreciated that the response is uniform over the main central area of the photocathode with a small border effect.

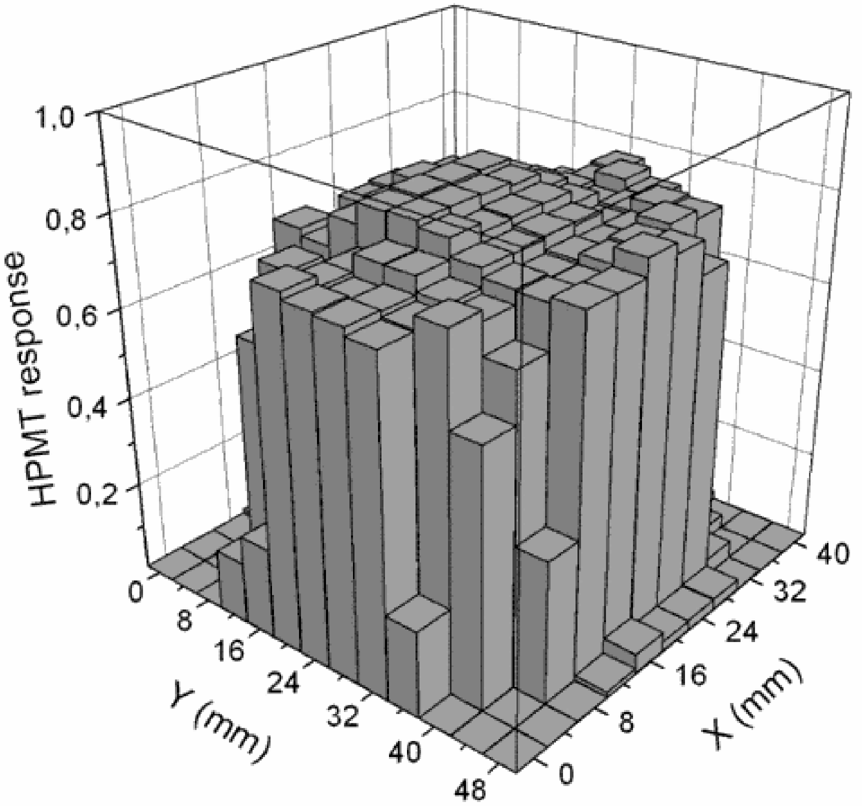

Figure 11 Histogram of 2D scan of the photocathode surface

CONCLUSIONS

Our results indicate that spherical diffuse reflectors of the minimum radius required by the vial size provide the best results in terms of collection efficiency. The effect of adding silicone grease to the vial-photocathode interface has not been tested and should certainly increase collection efficiency for configuration 2 (Horrocks 1964), especially if the volume of scintillator is small. This was not the aim of this work, which focused on using the most common working conditions with standard scintillation vials. It must be noted that the overall light collection efficiency also depends on the light transmission through the vial walls. This effect was only partially simulated in the work reported in this paper, with the light distribution outside the vials following experimental data (Durán Ramiro and García-Toraño 2005).

Since light distribution at the photocathode level and the HPMT response are homogeneous, the optical characteristics of the source and reflector are the main factors influencing light collection efficiency. Total counting efficiency will be also affected by the quantum efficiency of the phototube.

We expect that these results will contribute to the design of optimized reflectors for single photodetector LSC systems with improved total efficiency and energy resolution.

ACKNOWLEDGMENTS

The authors wish to thank Mr Frank Thim, Brandenburg GMBH, for his help and advice on utilizing LucidShape test version 1.3.

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