Improvement of Light Coupling in BGO Detector Module
by Optimization of the Crystal Shape*  
S.K. Hilal, Y.M. Ro*, C.W. Mun*, Y.S. Kim and Z.H. Cho*,**
Dept. of Radiology, Columbia Univ., 710W,168th St., New York, NY 10032

Abstract

Detector shape optimization study was carried out for the high resolution 4x4 array BGO-PMT coupling scheme to be employed in the spherical positron emission tomograph[1]. To improve the light collection efficiency in the BGO detector array, we have employed bullet nose shape BGO crystal in the front side as well as in the back side of detector the latter to be coupled to PMT's photocathode.

First, it is believed that the smooth and round front side bullet nose shape could eliminate the sharp corners of the crystal thereby improves the light collection efficiency. Secondly, the bullet nose shape at the back side of crystal which to be coupled to PMT will provide optimal coupling between the crystal and PMT by the focusing property of the bullet nose shape of the crystal.

Computer simulations and experimental study were carried out and results are reported.

Introduction

In the last several years, positron emission tomography performances have been improved substantially by improvement of the resolution and sensitivity by use of high stopping power scintillation crystals, namely BGO[2]. Recently, a number of positron emission tomography systems claim that their transaxial resolution are close to 3 mm FWHM by use of small size detector crystal[3]. Along with this trend, a number of small detector coupling schemes have been developed and are in use[4,5,6].

Smaller PMT, however, has the small uniform sensitivity area so that the efficiency as a function of the position on photocathode varies widely. Since smaller PMTs are used in most of the high resolution PET designs, the uniform optical coupling between the crystal and PMT and hence the sensitivity of PMT becomes worse. The coupling of small scintillation detectors to PMTs, therefore, has been a major importance for the high resolution PET design.

As discussed in section I, there are two points to be considered in the optimization of the shape of the crystal. One is related to the front side of crystal through which annihilation photons enter into the crystal thereby generate the light photons by the scintillation events and the other is the back side of the crystal where maximum light transmission to the PMT's photocathode is important. The latter usually requires optimal coupling between crystal and PMT.

1. Front side shape.

Once scintillation event occurs, light is generated isotropically in the crystal and reaches to the photocathode either
directly or indirectly after several reflections on the walls of the crystal. The reflection of the light on the diffused reflector is subject to Lambert's law given by following formula [10]

$$\frac{dI(\theta_r)}{dI_0} = \cos \theta_r$$

(1)

where $\theta_r$ is the reflection angle of the light with respect to the direction perpendicular to the surface and $I(\theta_r)$ and $I_0$ are the incident and reflected light, respectively (see Fig. 1(A)). Note that the intensity of light reflected on the diffused reflector surface is dependent only on the reflection angle (not on the incident angle) and is maximum at the vertical direction to the surface. Therefore, the shapes of the walls of crystal are strongly related to the total light output from the crystal. It is also noted that such as the corner of the crystal strongly traps the light. The optimal shape of the front-bullet nose is, therefore, designed to avoid possible light trappings as well as optimal reflection.

2. Back side shape.

The other point considered is related to the back side of the crystal where PMT is coupled. Since the refraction index of PMT window material, i.e., glass is less than that of BGO crystal, the angle of exit light from crystal is larger than the angle of incident light in crystal according to the refraction law of light

$$N_{BGO} \sin \theta_i = N_{Glass} \sin \theta_t$$

(2)

where $N_{BGO}$ and $N_{Glass}$ are the refraction indices of BGO and the glass of PMT and $\theta_i$ and $\theta_t$ are the angles of the incident and transmitted light, respectively. Because of these different refraction indices, it is expected that some loss of light in transmission process will occur at the contact surface between the flat crystal and the curved photocathode in PMT. The effect appears more serious when crystal is located at the corner of PMT than at the center because of the geometry of the photocathode in PMT. This is especially important in the case of 4x4 array detector coupling with two dual PMT to be used in S-PET design[5].

In addition to this geometrical factor, nonuniform-sensitivity characteristics of the PMT’s photocathode should also be considered to maximize the light output. For example, the sensitivity of photocathode at the corner of PMT is usually less than that of the center in PMT. It is necessary, therefore, to focus light onto the central region of PMT’s photocathode as much as possible. This requirement may be satisfied by forming the crystal again in a bullet-shaped nose and couple to the PMT’s photocathode. Actually, the bullet nose is working much like the convex lens which focuses the light into the focal point of lens.

We have obtained the optimal radii of both sides of crystal by Monte Carlo simulations. The S-PET system currently under development at Columbia university has modular detector system having a bundle of crystals(4x4 crystal array) on dual photocathode PMT (Hamamatsu's R2404) with the light coding scheme described in ref[5]. The size of each single crystal in the bundle is made of 4.4 mm (width) x 8.85 mm (height) x 55 mm (length) BGO. The geometrical location of crystals on PMT is shown in Fig. 2.

The procedure of Monte Carlo simulations are as follow.
1). The annihilation photons (511 Kev) are projected on the front side of crystal and scintillation events are generated within the crystal in random position with occurrence rate of scintillation events weighted by negative exponential which simply follows exp(-\mu \cdot \text{BGO} \cdot x), where \mu \cdot \text{BGO} is the attenuation coefficient of BGO and \( x \) is the path-length of the annihilation photon.

2). After each scintillation event, the direction of the light is randomly determined. When the light reflected at the crystal wall covered with diffused reflector, the reflected light direction is again randomly determined with weighting by Lambert's law as given in Eq. (1).

3). After a number of reflections, the light reaches at the back side of nose of the crystal which is in contact with PMT, the light intensity transferred to photocathode of PMT is thus determined by Fresnel equation which is given by

\[ T = \frac{2N_{\text{Glas}} \cdot \cos \theta_1 \cdot \cos \theta_2}{(N_{\text{Glas}} \cdot \cos \theta_1 + N_{\text{Glas}} \cdot \cos \theta_2)^2} + \frac{2N_{\text{Glas}} \cdot \cos \theta_1 \cdot \cos \theta_2}{(N_{\text{Glas}} \cdot \cos \theta_1 + N_{\text{Glas}} \cdot \cos \theta_2)^2} \]  \hspace{1cm} (2)

4). Finally the light output from the crystal which reached on the photocathode of PMT is weighted by the local sensitivity of photocathode. The projected annihilation photons are scanned the entire surface of the detector and summed to calculate the total efficiency of the detector system.

5). The procedures 1) through 4) are repeated.

**Simulations and Experimental Results**

Simulation results of the light collection efficiency of the BGO-PMT coupling indicate strong dependency on the radii of both sides of the BGO crystal. The simulated results of variations of light collection efficiency as a function of the radii of front side nose are shown in Fig. 3(A) and Fig. 3(B) for the horizontal and vertical direction, respectively. Results indicate the optimal radii of front side nose of crystal are 3.0 mm and 5.5 mm for horizontal and vertical direction, respectively. The variations of light collection efficiency as a function of various radius of the back nose are represented in Fig. 4(A) and Fig. 4(B) for the horizontal and vertical direction, respectively. The optimal radii of back nose of crystal were also found to be 3.0 mm and 5.7 mm for horizontal and vertical direction, respectively.

In order to verify the above simulation results, we have first measured the energy spectrum of crystal with the conventional flat shape as well as various bullet nose shapes. Same crystal which used in the first measurement of the conventional flat shape had been reshaped with optimal radii and the same experiment was performed. Energy spectra for the flat crystal (before shaping the crystal to bullet nose) and after bullet shaping are obtained and results are shown in Fig. 5. As seen Fig. 5, the relative light output of the peak points (511 kev) were 4.08 for the crystal at the corner of photocathode (set I) while 4.72 where the crystal was located at the center of photocathode (set II). This means that the crystal at the edge of PMT's photocathode (set II) is approximately 13% lower in sensitivity compared with that of the center (set I).

After optimal shaping of the both sides of crystal as bullet noses with the estimated optimal radii, the difference between set I and set II is reduced down to approximately 9% and the light output is also improved at the corner crystals more than 26% with improved resolution (from 34% to 32%). The experimentally measured light outputs with and without the bullet nose shaping in the set II are shown in Fig. 5.

**Conclusions**

The optimal shapes of the crystal (BGO) in the 4x4 array detector module with the light encoding scheme were studied through the simulations and experimental measurements. The light output of the crystal was improved by optimum shaping of crystal by bullet nose shapes. When the crystal is located at the corner of the photocathode, improvement of the light output was
Fig. 3. The relative light collection efficiency as a function of the radius of the bullet nose in the front side of crystal for ; (A) horizontal and (B) vertical direction.

Fig. 4. The relative light collection efficiency as a function of the radius of the bullet nose in the back side of crystal for; (A) horizontal and (B) vertical direction.

(A) 511 KeV peak = 4.08 (relative scale) with 34 % FWHM.

(B) 511 KeV peak = 5.15 (relative scale) with 32 % FWHM.

Fig. 5. Energy spectra for 511 KeV annihilation photon obtained from in set II (A) before shaping and (B) after shaping bullet nose with optimal bullet nose radius.

more pronounced and, thereby, the nonuniformity effects of photocathode were minimized. This is probably due to the fact that the back side (photocathode contact surface) bullet nose improves the light focusing to the central part of the photocathode thereby increased overall sensitivity.

References


