GlueX Note - 201 Issued: Feb. 16, 2007 Revised: May 3, 2007

#### Photon reconstruction in the FCAL

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#### Abstract

A photon reconstruction algorithm which provides efficiency for photons that enter the FCAL of 99.6%, and an energy resolution of 4% for 1 GeV photons, has been implemented in the GlueX analysis framework. The study of single photons, generated from the center of the target in the solid angle covered by the FCAL, revealed a high probability (37%) for photon conversion before FCAL. The conversion probability shows a strong angular dependence related to the presence of various detector components between the target and FCAL. The parts of the detector that have a large impact on pre-shower formation were identified. The effect of the TOF and steel plate in front of the FCAL on single photon resolution was found to be insignificant. Taking into account single clusters from photons that converted close to the FCAL face, the overall photon reconstruction efficiency was estimated to be 77

### 1 Introduction

The reconstruction of single photons in the GlueX forward electromagnetic calorimeter (FCAL) was studied employing the full GlueX detector simulation, based on Geant3. The FCAL consists of 2800 lead glass blocks each 45 cm long with a transverse size of 4 cm by 4 cm. Single photons were generated from the center of the target. The photon vertex was fixed at V=(0, 0, 63) cm, in the (x, y, z) system, and photons were generated uniformly in energy (E), from 0 to 10 GeV and in solid angle from polar angle ( $\theta$ ) from 0 to 12 degrees and full azimuth range. Shower simulation is currently based on a simple model that takes into account only energy deposition of particles in the lead glass and the attenuation of light along a FCAL block. Effects due to the Cerenkov light propagation and detection in a phototube will be incorporated at a later stage. All hits in the FCAL above the threshold, currently at 30 MeV, are recorded and used in subsequent analysis for photon reconstruction.

The photon reconstruction algorithm was developed at the University of Connecticut for the Radphi experiment. The algorithm groups hits in FCAL with more than 30 MeV into clusters, by selecting a highest energy block as a cluster seed and challenging every hit less than 25 cm away from the seed's center whether it can become a cluster member. The criteria for belonging to a particular cluster and what part of block energy contributes to the cluster energy is based on the shower profile function. A cluster can be formed from a minimum of two blocks with energy above the effective threshold of 50 MeV. The algorithm is described in more details in Ref. [1]. After clusters are formed, their energy and position need to be corrected due to the known shower depth and non-linear effects.

In addition to hits recorded in the FCAL, the HDGeant simulation provides information regarding Monte Carlo generated particles: Thrown (TH) and TrueShower (TS). In this analysis, a TH particle is a generated photon. TS particles are those responsible for shower formation. The value of the attribute 'primary' establishes correspondence between a TS and the TH photon. If this value is one, the TS particle originates from the primary vertex. In this analysis, the origin of TS is not recorded in the simulation, only the energy and position in the FCAL. Although it is possible to record the point of TS creation, following every TS particle through the detector can be costly in terms of simulation time. The results from the special simulation in which this feature was enabled can be found in GlueX-Doc-789 [2].

## 2 Shower reconstruction

The left plot in Fig. 1 shows energy of reconstructed clusters vs. generated energy, in the case where one cluster is found from one TS in the FCAL. A single conversion factor between cluster energy and hits in the FCAL was chosen to match photons at 1 GeV. Deviation from a straight line (solid) due to the non-linear energy response of the FCAL is evident. An



Figure 1: Cluster energy as a function of thrown energy before (left) and after (right) the energy non-linearity is taken into account. The solid red line corresponds to  $E_{reconstructed} = E_{generated}$ .

effective energy response function

$$E_{\gamma} = N \cdot E_c^{1-\epsilon},\tag{1}$$

can be used to reconstruct the photon energy,  $E_{\gamma}$ , from the cluster energy,  $E_c$ , where N is a normalization factor. The two competing processes, attenuation and shower leakage, have opposite effects on the non-linear factor  $\epsilon$ . The effective value of  $\epsilon$  depends on the part of the energy spectrum in consideration. At energies below 0.5 GeV the attenuation is dominating effect with  $\epsilon \approx 0.05$ . When photon energy increases, the core of the showers moves towards the downstream face of the FCAL. The shower leakage starts to play role for showers above 1 GeV and dominates above 5 GeV, resulting in  $\epsilon < 0$ . At this level of reconstruction, this dependence on energy is neglected and value of  $\epsilon = 0.03$  over the full generated energy range was obtained. After applying non-linear correction the distribution of reconstructed photon energy vs generated energy is shown in the right plot of Fig. 1.

Fig. 2 shows cluster energy resolution as a function of generated energy. The energy resolution has a negligible floor term and the statistical term of  $\approx 4\%$ . The intrinsic cluster resolution coming from the fluctuation in the number of shower particles is 3% and the systematic effect of averaging over the 10 GeV energy region with a constant non-linearity coefficient contributes additional 1%.

The right plot in Fig. 3 shows a plot of cluster polar angle for photons generated below  $10.6^{\circ}$ . Above this angle, photons hitting the BCAL can produce showers in the FCAL. The plot on the left of Fig. 3 shows polar angle resolution as a function of generated angle. Resolution at angles below  $2^{\circ}$  is effected by a digitization effect because the cluster position at the face of the FCAL is determined in terms of coordinates of the block center. The applied shower-depth correction does not have an angular dependence. In reality, polar angle, average shower depth and cluster energy affect each other and all are affected by the light attenuation and shower leakage [3]. This will be addressed at a later stage, after a



Figure 2: Photon energy resolution fitted with the standard expression for the lead glass resolution within the energy range indicated by the solid line.



Figure 3: Reconstructed polar angle (right) and angular resolution as a function of generated polar angle (left).

model that takes into account Cerenkov light propagation and collection at the downstream end of the FCAL block is finalized and incorporated into MC simulation.

The cluster multiplicity is plotted in the left plot of Fig. 4 for the case when only one TS (black) and more than one TS (red) particle was recorded in the FCAL. The presence of more than one TS in the FCAL indicates that initial photon converted before FCAL. The clustering algorithm is effective in reconstructing photons that did not convert before the FCAL. However, the clusterizer sometimes produces two clusters out of one generated photon. The angular distribution of thrown particles with a single TS and two clusters in the forward calorimeter is shown in the right plot of Fig. 4. This distribution of so-called splitoffs follow the same pattern observed in Radphi. The spike at low angle is associated with showers that leaked across the beam hole. The probability of splitting a shower increases with polar angle but it drops before the end of the FCAL acceptance because the number of



Figure 4: Cluster multiplicity (left) with one (black) and with many (red) TS in the FCAL. Angular distribution of split-showers  $(N_{TS} = 1)$  is shown on the right.

events with a single TS decreases due to the large pre-showering in this region (see Sect 3. Overall, less than 0.5% of photons that do not convert before the FCAL are reconstructed as two clusters.

## 3 Photon conversion

Fig. 5 shows the energy (left) and polar angle (right) distributions of thrown photons (black). Red histograms represent the same distributions when more than one cluster is reconstructed in the FCAL. Most of these events result from the conversion of initial photon into  $e^-e^+$ before it enters the FCAL. The spike in the red histogram at low angle is a beam-hole effect. The step in increasing the probability of pre-shower creation at  $\approx 7^0$  and a huge one at  $\approx 9^0$ will be examined. The initial suspects are FDC, CDC, and/or their signal cables.

Fig. 6 shows a 2D view of the GlueX detector, with three lines drawn from the center of the target at 7<sup>0</sup>, 9<sup>0</sup> and 12<sup>0</sup> respectively. The left plot on Fig. 7 shows generated photons flat in solid angle. The dotted histogram corresponds to the case when photon converts before it hits the FCAL. Vertical bars show angles at which significant change in conversion probability occurs. The right plot in Fig. 7 shows equivalent polar angle distributions. Overall probability for conversion of photons thrown in the FCAL aperture is  $\approx 37\%$ . Note the differences with respect to the right plot in Fig. 5 where events were generated uniform in angle and conversion of photons before the FCAL was indicated by counting multiple clusters instead of using MC true showers. The difference arises from the fact that 43% of converted photons do not produce multiple clusters because the conversion takes place close to the upstream face of the FCAL, for example, in TOF. The distribution of pre-showers in azimuth is uniform, with only 3 small holes  $\approx 4^0$  wide at 90, 210 and 340<sup>0</sup>.



Figure 5: Energy (left) and polar angle (right) distributions of generated photons (black). Multi cluster reconstruction in the FCAL (red) corresponds to the case when multiple TS were generated due to conversions.



Figure 6: Detector view in the y-z plane with the scale in y doubled. The tree lines correspond to polar angles of 7<sup>0</sup>, 9<sup>0</sup>, and 12<sup>0</sup> viewed from the center of the target.



Figure 7: Distribution of photons generated uniformly in solid angle (left). The dotted line corresponds to the case when more than one TS was found in the FCAL indicating photon conversion before the FCAL. Corresponding polar angle distributions are shown in the right plot. Significant changes in the conversion probability are labeled by vertical lines.

#### **3.1** Impact of the material on photon conversion

Fig. 8 shows the impact of various detector components on photon conversion probability in front of the FCAL. Colored curves were obtained after removing or turning into air the material of those sub-systems that showed a large effect on photon conversion. The biggest impact on photon conversion before the FCAL, comes from the FDC rings. Photons thrown at angles above 10.8<sup>0</sup>, i.e. outside the FCAL aperture, can still produce showers in the FCAL even after removing the FDC supporting material.

#### **3.2** Impact of the TOF and FCAL Steel plate on photon resolution

Fig. 9 shows energy resolution of single clusters reconstructed from photons that hit the FCAL, which were generated in polar angles of  $1^{0}-9^{0}$  (left) and  $9^{0}-10.5^{0}$  (right). The solid circles and triangles correspond to 1.0 in and 2.0 in total thickness of the two TOF scintillating plates, respectively. Open circles and triangles represent the case when 0.5 *in* steel and 0.5 *in* Plexiglas plates were put in between the TOF and the FCAL in addition to the setting with 2 *in* total thickness of the TOF scintillating material. The sheet of steel is proposed for magnetic shielding and to reduce radiation exposure of the FCAL, in a similar fashion as in the E852 experiment, while the Plexiglas sheet will be used to distribute light from a laser for gain monitoring of the FCAL blocks during the run, as used in both E852 and Radphi experiments. As expected, these four different settings did not affect the resolution for photons that did not convert before hitting the FCAL.

Fig. 10 shows the energy resolution for photons that converted before entering the FCAL



Figure 8: Photon conversion probability as a function of generated angle. Colors represent the effect of turning into air some of the material in the detector.

but still produced a single cluster. For clarity purposes only two settings are shown, with the same labeling as in Fig. 9. Although most of the photons thrown between  $1^{0}$ - $9^{0}$  (left plot) converted in TOF some of them probably converted earlier and part of their energy was lost. This resulted in degraded energy resolution for low energy photons (solid triangles). Adding the steel plate in front of the FCAL increased the relative number of photons that converted close to the FCAL face which improved the resolution compared to the case when only TOF was in front of the FCAL. For photons thrown at larger angles (right plot) the effect of steel plate is visible only for those with energy above 2.5 GeV. The Plexiglas sheet did not have a significant effect on photon resolution.

Fig. 11 shows the energy resolution for all reconstructed single clusters (black circles) with the material in front of the FCAL listed in Figs. 9- 10 (open triangles). The effective resolution at 1 GeV is 5% and the overall efficiency for finding one cluster in the FCAL is 77%, when the fiducial cut on thrown photons is applied ( $0.8^{\circ} < \theta_{MC} < 10.6^{\circ}$ ) Contributions from single clusters reconstructed when photons converted before (16% of time) and after (61% of time) hitting the FCAL are shown by red and blue circles, respectively. The rest of the thrown photons (23%) either produced more then one cluster or did not satisfy criteria for becoming a cluster (see Sec. 1). At energies below 1.5 GeV, clusters from photons that converted have slightly degraded resolution. However, at energies above 4 GeV, the presence of the steel in front of the FCAL improves the resolution by increasing the pre-showering and reducing the shower leakage at the downstream end of the FCAL.



Figure 9: Single cluster energy resolution for photons that entered the FCAL within the polar angle of  $1^{0}-9^{0}$  (left) and  $9^{0}-10.5^{0}$  (right), for four different detector settings (see text for explanation).



Figure 10: The same as Fig. 9 for single clusters reconstructed after photon conversion in front of the FCAL and only two detector settings (see text).



Figure 11: Energy resolution of all single clusters (black circles) obtained with total 2 *in* thickness of TOF and 0.5 *in* of steel and Plexiglas in front of the FCAL. Resolution of single clusters from photons that did not convert (blue circles) and from photons that converted before the FCAL (red circles) are shown for comparison.

# 4 Recovery of converted photons

In the case when two clusters are found in the FCAL, it is possible to sum their energies to recover the thrown energy. However, this will be a challenge in the environment of the real experiment, especially for more than two clusters. Fig. 12 shows the fraction of reconstructed cluster energy (colored boxes) as a function of total generated energy. The summed energy is shown by black dots. The plot on the right shows the distance of clusters as a function of generated polar angle. All plots correspond to photons generated uniformly in solid angle.

Fig. 13 shows the summed energy resolution of two clusters for the two ranges of generated polar angle. The presence of the steel and Plexiglas does not affect the two-cluster resolution substantially. Fig. 13 also shows that recovering photons below 300 MeV will be impossible.

Fig. 14 shows longitudinal (U) and transverse (V) distance of two clusters from the projected position of the generated photon at the FCAL mid-plane, i.e. if the photon did not convert before the FCAL. The U-V coordinates were obtained by rotating the cluster position in the x-y plane around the azimuth of the generated photon  $\phi_{MC}$ . In this system, the coordinates of the generated photon are  $U_{MC} = r_{MC}$ ,  $V_{MC} = 0$ , where  $r_{MC}$  is the radial distance from the beam axis taken, at the mid-plane. This shows that a high/low energy pair of clusters at large angles, separated less than 15 cm, could be recombined to recover the energy. Information from other detectors such as the FDC, can be used to help in determining the origin of the pair and consequently the original photon momentum.



Figure 12: Fraction of energy of two clusters (red and blue) and the sum of their energy (black dots) as a function of generated energy (left). Distribution of two-cluster separation as a function of generated polar angle is shown on the right.



Figure 13: The same as Fig. 10 for the summed energy of two clusters reconstructed after photon converted in front of the FCAL.



Figure 14: Longitudinal (left) and transverse (right) distance of two clusters from the point of the intersection of the thrown photon direction and the FCAL mid-plane.



Figure 15: The longitudinal (top) and transverse (bottom) size of regular clusters ( $N_{TS} = 1$ ) as a function of thrown energy (left) and polar angle (right).

#### 4.1 Cluster size

One might explore the idea of using cluster size to select candidates for recombination. Fig. 16 shows the cluster size (*rms*) from photons that did not convert before the FCAL, measured along the radial direction (longitudinal size) and perpendicularly to the radial direction (transverse size) of the cluster centroid as a function of generated energy (left) and angle (right). Transverse size is almost constant and the longitudinal size is flat in energy above 3 GeV. The longitudinal size slightly increases with polar angle. Similar features of MC showers were observed in Radphi, before proper model for Cerenkov light collection was developed.

The same quantities were calculated for clusters reconstructed in the simplest multi-cluster case of photon conversion, i.e. when only two clusters are found in the FCAL. As an example, the longitudinal and transverse size of the second cluster vs cluster energy (left) and polar angle (right) is shown in Fig. 16. The size of these clusters follows the same pattern observed for regular clusters shown in Fig. 15. It appears that these clusters are not significantly larger than regular clusters.

In general, it is possible to recover photons that produced two clusters in the FCAL since most of the time full energy is deposited. This would push the single photon reconstruction efficiency above 85%. However, recovery of the position and thus momentum will be difficult and information from other detector systems will help. The cluster size does not appear to be distinguishing feature of those multi-clusters that can be used for their recombination. In order to increase the photon reconstruction efficiency algorithms need to be explored with realistic physics and background.



Figure 16: The same as Fig. 15 for the second (less energetic) cluster of two clusters.

# 5 Conclusions

Full detector simulation of single generated photons was performed with different detector settings. The simulation includes only statistical effects from shower development and not from photon propagation and detection. The reconstruction algorithm, imported from the Radphi experiment, showed good efficiency for reconstructing photons that enter the FCAL. Only a small fraction of generated photons are split due to the shower fluctuations in the lead glass. However, a considerable fraction of generated photons converts in the material between the target and FCAL. The biggest impact on pre-shower creation was supporting material in the FDC. The ongoing re-design of the FDC support material will result in decrease of the mass seen by photons from the target, which will reduce conversion probability. A fraction of those conversions resulted in the multi-cluster reconstruction in the FCAL while some times single clusters were produced, presumably from photons that converted close to the FCAL face. The energy resolution of those clusters was not affected by doubling the amount of scintillating material in the TOF. Inserting the steel plate also did not affect substantially the resolution of low energy photons compared to the case when there was no conversion before the FCAL. However, it reduced the shower leakage and consequently improved the resolution for high energy photons.

Photons that convert early produce multiple clusters that might be recombined to recover photon energy, based on the summed cluster energy, their position and separation in the FCAL. However, it will be difficult to identify candidates for recombination without help from other detector components. The size of those clusters compared to the size of regular cluster is not significantly different to be used as a selection criterion. Algorithms need to be explored with realistic physics and backgrounds to increase the photon reconstruction efficiency.

# References

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