Simulation of the Electromagnetic Calorimeter in CLAS12

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October 31, 2011

Abstract

We describe here the forward electromagnetic calorimeter (EC) that will be part of the base equipment for the CLAS12 detector in Hall B at Jefferson Lab. CLAS12 is being built to take advantage of the new physics opportunities opened by the 12 GeV Upgrade at Jefferson Lab. Robust, accurate simulations of the detector are essential to keep systematic uncertainties low. We have developed a new, physics-based simulation called gemc that uses the Geant4 package to simulate the interaction of particle with matter. We describe here the implementation of the EC in gemc including the geometric model, how it is was applied in gemc, the simulation of raw signals, and their digitization. We show results of tests of the package including comparisons with previous simulations of the EC and measured properties.

1   Introduction

In this CLAS-Note we describe the implementation of the forward electromagnetic calorimeter (EC) in `gemc`, the CLAS12 simulation package. The purpose of the EC is (1) detection and triggering of electrons, (2) detection of photons (for reconstruction of other particles like π^0 and η), and (3) neutron detection. The information from the EC will be combined with data from the two threshold Cherenkov detectors (the high-threshold Cerenkov counter (HTCC) and the CLAS6 Cerenkov counter (CC)) to provide high electron detection efficiencies and large hadron rejection factors. The EC is an electromagnetic sampling calorimeter that consists of six, identical sectors and covers the forward region ($5° < \theta < 45°$) of each CLAS12 sector. The CLAS6 forward electromagnetic calorimeter will be reused in CLAS12 largely without modifications [1]. Relevant details can be found in Section 1.

Simulation of CLAS12 is an essential part of the design of the detector and is needed for the analysis of CLAS12 data. The precision of many experiments will be be limited by systematic uncertainties instead of statistical ones, so an accurate simulation is vital [2]. A robust, maintainable simulation for CLAS12 `gemc` is now being developed [3]. In this paper we will describe in broad terms the CLAS12 forward electromagnetic calorimeter and then focus in great detail on the EC geometry. We then describe how this geometric information in implemented in `gemc` and our initial results measuring the features of the EC with the new simulation (*e.g.* sampling fraction,...) and conclude with a summary.

2   Description of the Electromagnetic Calorimeter

The EC is an electromagnetic sampling calorimeter that covers the forward region ($5° < \theta < 45°$) of each CLAS12 sector [4]. It is constructed from alternating layers of scintillator strips and lead sheets, with a total thickness of 39 cm of scintillator and 8.4 cm of lead, for a total thickness of 16 radiations lengths. The module construction is illustrated in Fig 1.

The lead sheets account for 90% of the 16 radiation length thickness. In each module, the scintillator/lead layers are contained in a volume having the shape of a nearly equilateral triangle. Each module contains 39 layers consisting of $10-mm$ thick scintillator and 2.2 mm of lead. The module was designed using a projective geometry, pointed at the nominal CLAS6 target position, such that the solid angle subtended by successive layers is approximately constant for the CLAS6 configuration. The entire detector will be placed about 200 cm further away from the nominal CLAS12 target position than the CLAS6 target position. The azimuthal (ϕ) coverage ranges from about 50% at forward angles to approximately 90% at large angles. Each layer consists of 36 scintillator strips oriented parallel to one side of the triangle, with the strip orientation being rotated by $120°$ in each successive layer (labeled U, V, and W in Fig 1).

The three orientations (or views) of scintillator strips are labeled u,v and w. Each view contains 13 layers, which are subdivided into inner (5 layers) and outer (8 layers) stacks that provide longitudinal sampling. Each of the view/stack combinations are optically ganged and coupled to XP2262 PMTs via fiber optic cables. The optical readout of the EC is illustrated in Fig 2 (same electronics in CLAS12??). The 1296 PMT channels are read out by FASTBUS crates containing LeCroy 1881M ADC and LeCroy 1872A TDC boards.
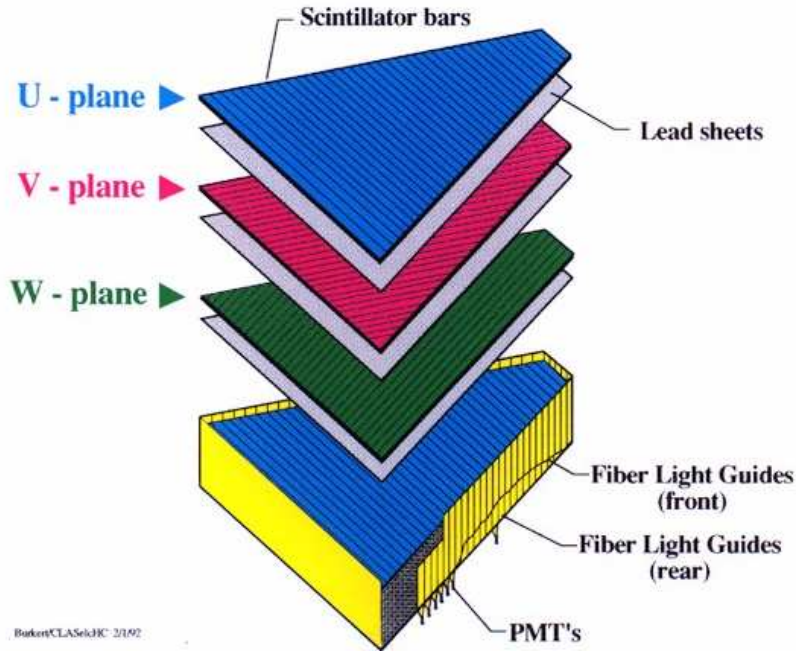
Figure 1: Exploded view of the electromagnetic calorimeter

Leading edge discriminators are used to provide timing signals to the TDC.

To reconstruct a hit in the EC in CLAS6, energy deposition is required in all 3 views of either the inner or outer layers of the module. Adjacent strips are placed into groups in each view if their deposited energy is above a software threshold. After grouping, the centroid and RMS for each group are computed. The intersection points of scintillator groups in different views are found. Intersections which contain groups from all 3 views correspond to hits. The energy deposit and time of the hit are calculated taking into account the path lengths from the hit location to the readout edge (to correct for signal propagation time and attenuation). If one group is involved in more than one hit, its energy is divided between hits with an appropriate weighting. A view of the CLAS6 EC showing reconstructed hits is shown in Fig 3.

3 EC Geometry

In defining the CLAS12 EC geometry we draw on our experience with the CLAS6 version. Our description relies heavily on the work of R. Minehart [5]. However, it is not identical (although the actual detector is) to Ref. [5], because we generate the parameters used by Geant4 to build the detector simulation in gemc [6]. Geant4 is a toolkit for the simulation of the passage of particles through matter and is one of the essential pieces of the CLAS12 simulation. We do use the same notation as Ref [5] when it is appropriate.

We define here two coordinate systems needed to incorporate the EC geometry into *gemc*. For each sector of the EC we define a coordinate system we call the G4 sector
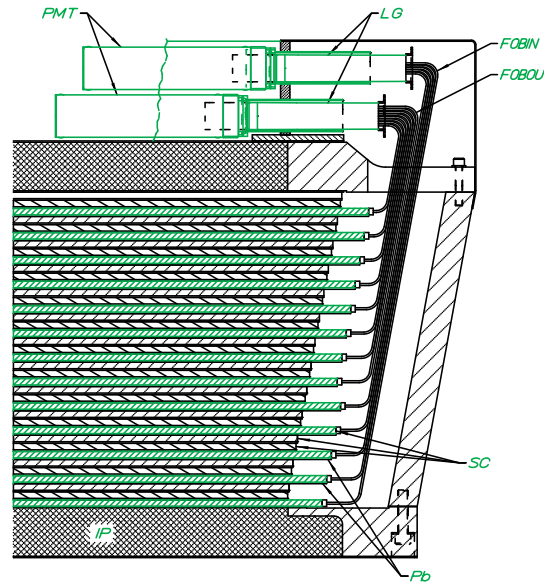
Figure 2: Side view of EC module, showing optical connections.
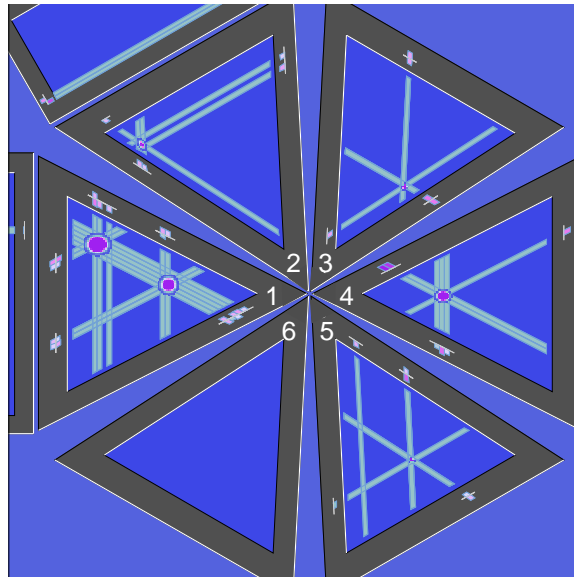
Figure 3: Event reconstruction in the EC. In sector 2,3,4,5 a single hit is found, while in sector 1, multiple hits are reconstructed.

coordinate system. These coordinates are different from the usual sector coordinate system used in, say, the drift chamber geometry, but they are consistent with the local EC coordinate system that is centered on the individual detector and used in Geant4 to define the volume of the detector. The z axis of the G4 sector coordinates is horizontal along the beam line and in the direction of the beam. The y axis is pointed radially outward from the beamline and lies in the ideal midplane of the EC. The x axis is constructed to form a right-handed

coordinate system. We define (for later use) the 'perpendicular point' P by a line drawn from the target point T at the origin (and nominal target center) to a point on the face of the first scintillator layer and perpendicular to that face. See Fig 4.

The G4 local EC coordinate system has its origin at the geometric center of the triangle formed by the three sides of the front face of the first scintillator (closest to the target) of the EC. The z axis of the G4 local EC coordinates is perpendicular to the face of the detector (and hence parallel to the line from the target point T to the perpendicular point P) and points away from the target. The negative y axis is parallel to the face of the first scintillator layer, passes through the origin, and passes through the vertex of the triangle-shaped scintillator layer that is closest to the beam line (small polar angle θ). The positive y axis passes through the origin and through the center of the side of the triangle farthest from the beam. It is also parallel to the face of the first scintillator layer. The x is oriented to form a right-handed coordinate system. The positive x axis points to the left as one is looking outward from the target (*i.e. downstream*) and along the z axis of the G4 local EC coordinates. Note that the y axis for both the G4 sector coordinates and the G4 local EC coordinates lie in the same plane.

We now begin constructing a description of the EC geometry. The nominal distance from the target point T at the CLAS12 target center to P is $L_1 = 7217.23\ mm$. The front face (and all the layers)of the EC makes an angle $\theta_{EC} = 25°$ to a line perpendicular to the beam line so we construct a vector $\vec{L}_1$ in the G4 sector coordinate system

$$\vec{L}_1 = (0, L_1 \sin\theta_{EC}, L_1 \cos\theta_{EC}) = (0, 3050.13\ mm, 6541.03\ mm) \qquad (1)$$

which goes from the target point T to P. Next, we construct a second vector $\vec{S}$ that goes from P to the geometric center of the face of the EC scintillator (closest to the target)

$$\vec{S} = (0, -y_{PO} \cos\theta_{EC}, y_{PO} \sin\theta_{EC}) = (0, -861.79\ mm, 401.86\ mm) \qquad (2)$$

where $y_{PO} = 950.88\ mm$ is the distance from the CLAS12 perpendicular point P to the geometric center of the front face of the first scintillator. See Fig 4. The distance y_{PO} is the length of the vector $\vec{S}$ in Fig. 4.

In the G4 local EC coordinate system we treat the active area of each EC layer as a triangle and define this triangle in terms of a trapezoid in Geant4. The y position of the geometric center of layer L is at

$$y_{cent}(L) = a_1(L - 1) \qquad (3)$$

where $a_1 = 0.0856\ mm$ and the units of $y_{cent}(L)$ are mm. Note that for $L = 1$, the center of the face of the scintillator is at the origin. The half-height in the y-direction (half the distance from the vertex closest to the beamline to the center of the opposite side of the triangle) is

$$\Delta y(L) = a_2 + a_3(L - 1) \qquad (4)$$

where $a_2 = 1864.65\ mm$, $a_3 = 4.45635\ mm$, and the units of $\Delta y(L)$ are mm.

To define a scintillator layer in Geant4 we need the half-width in the x direction at the vertex of the triangle closest to the beam (where it is zero) and the half-width in the
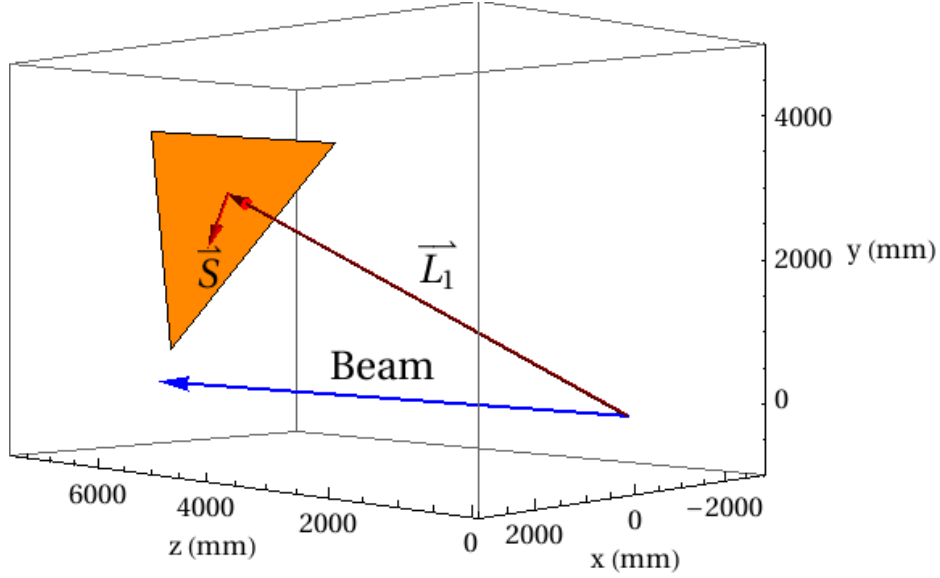
Figure 4: Drawing of the active area of the front face of the first EC scintillator. The vectors $\vec{L}_1$ and $\vec{S}$ determine the geometric center of the scintillator face. The G4 sector coordinate system is shown. The distance y_{PO} discussed in the text is the length of $\vec{S}$.

x direction on the side of the triangle farthest from the beam (Δx). The active triangular region is bounded by three lines:

$$y = y_{cent}(L) - \Delta y(L) + (-\tan\theta_o)x \tag{5}$$

$$y = y_{cent}(L) - \Delta y(L) + (+\tan\theta_o)x \tag{6}$$

$$y = y_{cent}(L) + \Delta y(L) \tag{7}$$

where $\tan\theta_o = 1.95325$ and $\theta_o = 62.889°$ is the angle between sides of the triangle on the outside edge of the calorimeter (at large polar angle). Equations 5-6 define the left- and right-hand sides of the triangular active area of the first scintillator (as one looks outward from the target) and Equation 7 defines the outer edge of the active area of the first scintillator layer (at large polar angle θ). The half-width in the x direction on the side of the triangle defined by Equation 7 (the side of the triangle farthest from the beam) is

$$\Delta x = \frac{2\Delta y}{\tan\theta_o} \tag{8}$$

where Δy is defined in Equation 4. We also need the half-width in the z direction. The thickness of each layer is constant at 12.38 mm so

$$\Delta z = \frac{12.38\ mm}{2} = 6.19\ mm \qquad . \tag{9}$$

To define the geometry of the strips in each layer we start with the y coordinate of the lower edge of a U strip in layer number L. In Fig. 5 we show the orientation of a single
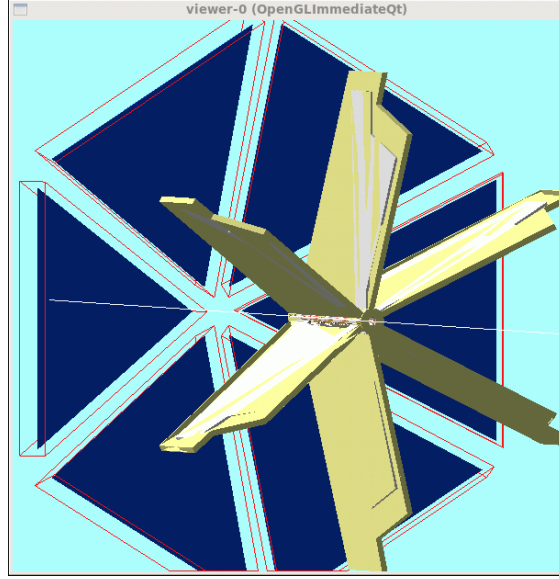
Figure 5: Display of a single layer (layer 17) from the EC for all six sectors (dark, blue triangles). The white line defines the beam axis and the torus is shown for comparison. The red wireframe is the EC mother volume.

EC scintillator layer in all six sectors. The white line marks the beam axis and the torus is shown to orient the reader. In the G4 local coordinates the lower edge of a U strip in layer number L is given by

$$y = -a_2 - a_4(L - 1) + (U - 1)w_u(L) \tag{10}$$

where a_2 is defined above, $a_4 = 4.3708 \ mm$, and

$$w_u(L) = a_5 + a_6(L - 1) \tag{11}$$

is the strip width for the U strips in layer L and $a_5 = 103.655 \ mm$ and $a_6 = 0.2476 \ mm$. Equation 10 is for the y coordinate for the lower edge of the U strip. The upper edge of the strip is obtained by setting $U = U + 1$.

The edges of the V strips are given by the equation

$$y = y_{cent}(L) - \Delta y(L) + w_v(L)(37 - n)\sqrt[2]{1 + \tan^2 \theta_o} - \tan \theta_o x \tag{12}$$

and the edges of the W strips are given by

$$y = y_{cent}(L) - \Delta y(L) + w_w(L)(37 - n)\sqrt[2]{1 + \tan^2 \theta_o} + \tan \theta_o x \tag{13}$$

where n is the strip number ($n = n_{min} = 1$ is the shortest strip and $n = n_{max} = 36$ is the longest). The widths of V and W strips are given by

$$w_v = a_7 + a_8(L - 2) \tag{14}$$

where $a_7 = 94.70 \ mm$ and $a_8 = 0.2256 \ mm$ and

$$w_w = a_9 + a_8(L - 3) \tag{15}$$

where $a_9 = 94.93 \ mm$ and $a_8 = 0.2256 \ mm$. Each strip has a trapezoidal portion on its light collection end that extends beyond the triangular region defined above. The trapezoid has right angles at the end of the strip, and distance from the end to the triangular region is given by two distances.

$$d_2 \qquad and \qquad d_1 = d_2 + \frac{w}{2}\left(\frac{\tan^2(\theta) - 1}{\tan(\theta)}\right) \qquad (16)$$

where w is the width of the strip. For the first 15 layers

$$d_2 = 36.4 \ mm, \qquad L \leq 15 \qquad (17)$$

and for the remaining layers

$$d_2 = 25.4 \ mm, \qquad L > 15. \qquad (18)$$

The z spacing between layers is (according to Cassim Riggs) 12.381 mm which is $2\Delta z$ so that the total depth of the detector along the z direction is

$$\Delta z_{total} = 2(n_{max} - 1)\Delta z + 2\Delta z_{scint} \qquad (19)$$

where $\Delta z_{scint} = 5 \ mm$ is half the thickness of the plastic scintillators and $n_{max} = 36$ as before so the z coordinate of the front face of each layer of scintillator is

$$z(L) = -\frac{\Delta z_{total}}{2} + 2\Delta z(L - 1) \qquad (20)$$

The calorimeter can be viewed as being subdivided into triangular stacks, each one directed back towards the target. A convenient labeling for these stacks is provided by the number N, where

$$N = U(U - 1) + V - W + 1 \qquad (21)$$

subject to the subsidiary condition for a valid combination that

$$S = U + V + W = 73 \ or \ 74 \qquad (22)$$

With this numbering scheme, the cell #1 is at the vertex near the beam, with $U = 1, V = W = 36, \ and \ S = 73$. The final cell in this scheme is at $U = V = 36$, $W = 1$, for which $N = 36^2 = 1296$. In general, if $U + S = 2U + V + W$ is even(odd) the triangular cell points toward(away from)the beam. The center of the cell is at

$$y = -a_2 - a_4(L - 1) + (U - 0.5)w_u(L) \qquad (23)$$
$$x \tan \theta = (W - V)w_u(L) \qquad (24)$$

or

$$x = \frac{1}{\tan \theta_o}(W - V)w_u(L) \qquad (25)$$

.

The parameters defined in the text above are summarized in Table 1 below.

Name	Value	Name	Value
θ_{EC}	25°	θ_o	62.88°
a_1	0.0856	a_2	1864.6
a_3	4.45635	a_4	4.3708
a_5	103.66	a_6	0.2476
a_7	94.701	a_8	0.2256
a_9	94.926		

Table 1: Table of coefficients for equations in text.

4   Adding the Forward Electromagnetic Calorimeter to gemc

In this section we summarize the current, physics-based CLAS12 simulation program called gemc, go through the steps required to add the EC to gemc and show some initial results. The physics-based CLAS12 simulation program `gemc` is a modern, object-oriented code. It is based on the C++ programing language and Standard Template Libraries for constructing objects. The parameters that define a particular simulation (geometry, materials, magnetic fields, step size, *etc.*) are stored external to the code and most are saved in a mysql database. This enable users to rapidly change the parameters of the simulation without having to re-compile the code. The factory method is used for the processing individual hits in CLAS12, for digitizing those hits to mimic the data stream, and for the defining the input/output formats. We are using the Geant4 package from CERN for handling the passage of particles through matter [6]. Geant4 (for GEometry ANd Tracking) performs this task using Monte Carlo methods and is the successor to Geant3. It is the first such package to use object oriented programming, is written in C++, and is well supported by CERN and the international Geant4 Collaboration. Geant4 includes facilities for handling geometry, tracking, detector response, run management, visualization and user interface.

The first step in adding the EC to gemc is to define the EC geometry using Geant4 and the CLAS12 mysql database. Geant4 provides methods for defining the physical volumes that make up the CLAS12 simulation and the information needed for a particular CLAS12 component is read from the database. For the EC we are using a generalized trapezoid (G4Trap method in Geant4) to represent the mother volume which encloses the entire EC module and to describe each scintillator or lead layer of the detector. The strips that make up each scintillator layer are not defined until the digitization phase. The Geant4 parameters for G4Trap are shown in Table 2 and Fig 6 shows the generalized trapezoid. We use the same axes definitions as Geant4 for our G4 local EC coordinate system.   To define this geometry a Perl script (`ec_build.pl` in the area `gemc/production/database_io/clas12/geo/ec`) generates a file containing the mysql code needed to modify the mysql database which is called by a shell script (`go_table`).

The second step is to define the data banks that will be stored in the mysql database used for the EC. In the subdirectory `gemc/production/database_io/clas12/banks/bankdefs` a file `EC.bank` defines the quantities that will be generated in the simulation (see Table 3).

Name	Description	Name	Description
$pDx1$	Half x length of the side at $y = -pDy1$ of the face at $-pDz$	$pDx2$	Half x length of the side at $y = +pDy1$ of the face at $-pDz$
$pDx3$	Half x length of the side at $y = -pDy2$ of the face at $+pDz$	$pDx4$	Half x length of the side at $y = +pDy2$ of the face at $+pDz$
$pPhi$	Azimuthal angle of the line joining the center of the face at $-pDz$ to the center of the face at $+pDz$	$pTheta$	Polar angle of the line joining the centers of the faces at $\pm pDz$
$pDy1$	Half y length at $-pDz$	$pDy2$	Half y length at $+pDz$
$pAlp1$	Angle with respect to the y axis from the center of the side (lower endcap)	$pAlp2$	Angle relative to the y axis from the center of the side (upper endcap)
pDz	Half z length		

Table 2: Geant4 parameters for the G4Trap volume.

Note that while we defined the geometry above in terms of layers, in the real detector, we do not measure the properties of a track layer by layer. The first fifteen scintillator layers are ganged together to form the 'inner' calorimeter and the remaining twenty-four layers form the 'outer' calorimeter. This information (inner versus outer) is stored in the 'stack' parameter in Table 3. We also record the orientation of the strips, the U, V, or W view, for each hit. Recall Fig 1.

The file `clas12_hits_def.txt` in `gemc/production/database_io/clas12/banks` was modified to add the information necessary for the EC. Executing the shell scripts `go_table` followed by `go_hits` puts the information in the mysql database. In the subdirectory `gemc/production/hitprocess/` we created the file `EC_ hitprocess.cc` (which contains the functions that process the hit) and the header file `EC_ hitprocess.h` (which declares those functions) to process the simulation information and form hits. To add these functions to `gemc` we edited the file `HitProcess_MapRegister.cc`. After these steps `gemc` was recompiled.

The last step in adding the EC to gemc is to digitize the signals produced in the simulation. The geometry of each scintillator layer in *gemc* is one large sheet. In CLAS12 it will be made of separate strips. To determine which strip a particular track has struck consider Figure 7. The track has struck the layer at the point $\vec{P} = (x, y)$ (the hit). The corners of the triangle (points A, B, and C) can be written down in terms of the Geant4 parameters (see Table 2).

$$\vec{A} = (x_A, y_A) = (0, -pDy1) \tag{26}$$

$$\vec{B} = (x_B, y_B) = (pDx2, pDy1) \tag{27}$$

$$\vec{C} = (x_C, y_C) = (-pDx2, pDy1) \tag{28}$$

With this information in hand we calculate $\vec{r_1} = \vec{P} - \vec{C}$ and construct the unit vector $\hat{r}_2$ so that it is perpendicular to a vector going from A to B (*i.e.* $\vec{B} - \vec{A}$) so

$$\hat{r}_2 = \frac{(y_B - y_A, x_A - x_B)}{\sqrt{(y_B - y_A)^2 + (x_A - x_B)^2}} \tag{29}$$
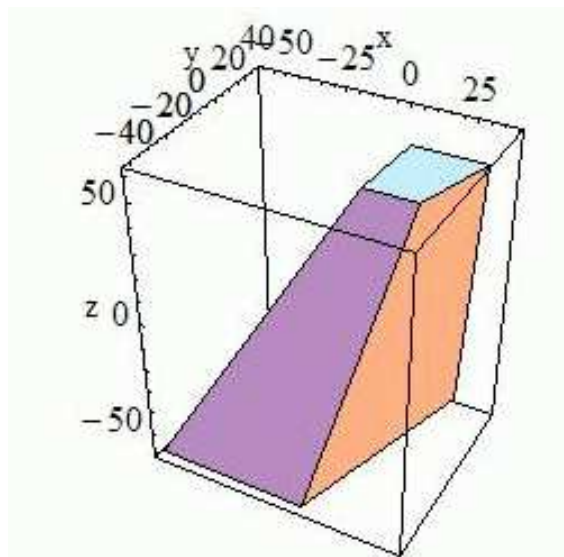
Figure 6: Geant4 generalized trapezoid.

Name	ID	Type	Activated	Description
ETot	1	1	1	Total Energy Deposited
$< x >$	2	1	1	Average global x position
$< y >$	3	1	1	Average global y position
$< z >$	4	1	1	Average global z position
$< lx >$	5	1	1	Average local x position
$< ly >$	6	1	1	Average local y position
$< lz >$	7	1	1	Average local z position
$< t >$	8	1	1	Average time
pid	9	1	1	Particle ID
vx	10	1	1	x coordinate of primary vertex
vy	11	1	1	y coordinate of primary vertex
vz	12	1	1	z coordinate of primary vertex
E	13	1	1	Energy of the track at the entrance point
mpid	14	1	1	Mother Particle ID
mvx	15	1	1	x coordinate of mother vertex
mvy	16	1	1	y coordinate of mother vertex
mvz	17	1	1	z coordinate of mother vertex
sector	18	0	1	sector
stack	19	0	1	stack
view	20	0	1	view
strip	21	0	1	strip
EC_ADC	22	0	1	EC ADC
EC_TDC	23	0	1	EC TDC

Table 3: Contents of `EC.bank` which is used to define the EC banks.

V View from Target
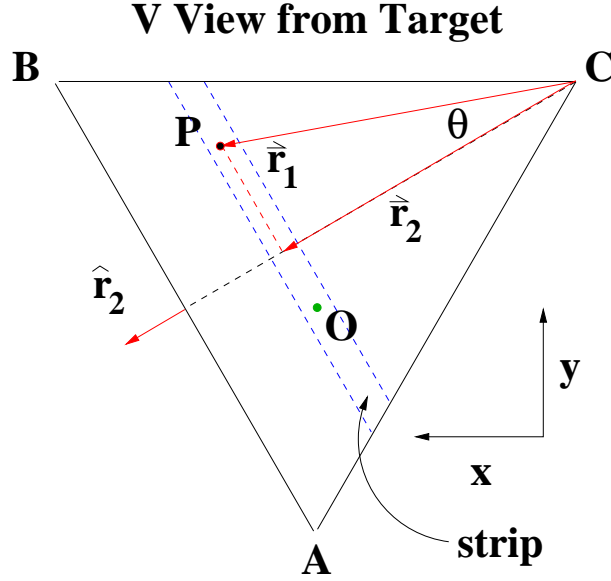
Figure 7: Front view of V layer showing quantities needed to determine the strip of a hit at point P.

and

$$\cos\theta = \frac{\vec{r}_1 \cdot \hat{r}_2}{|\vec{r}_1|} \qquad . \tag{30}$$

We then calculate the length of the vector $\vec{r}_2$ in Figure 7 which is the distance to the hit perpendicular to the orientation of the V strips. This length is

$$|\vec{r}_2| = |\vec{r}_1|\cos\theta \tag{31}$$

so the strip number is the following

$$strip = \lfloor \frac{|\vec{r}_2|}{36} \rfloor + 1 \tag{32}$$

where the first term on the right-hand side is the greatest integer less than or equal to $|\vec{r}_2|/36$.

Once we have the strip number we can calculate the expected ADC signal and the photon attenuation. For each hit we convert the deposited energy into photons at a rate 3.5 photons/MeV and use this value to form a Poisson distribution. The number of photons is chosen randomly from this Poisson distribution. The attenuation of the photons as they propagate down the strip is calculated using the known attenuation factor $\lambda_0 = 3760\ mm$ and the distance from the hit to the light guide on the end of each strip. The geometric quantity needed to calculate this distance is the length of the vector $\vec{r}_V$ in Figure 8 which goes from the position of the hit at point P in a direction parallel to the line segment $\overline{AB}$ to the end of the strip. The vectors for the corners of the triangle, points A, B, C are the same as those above. The equation for the line segment $\overline{BC}$ is the following.

$$y = y_{BC} = pDy1 \tag{33}$$

V View from Target
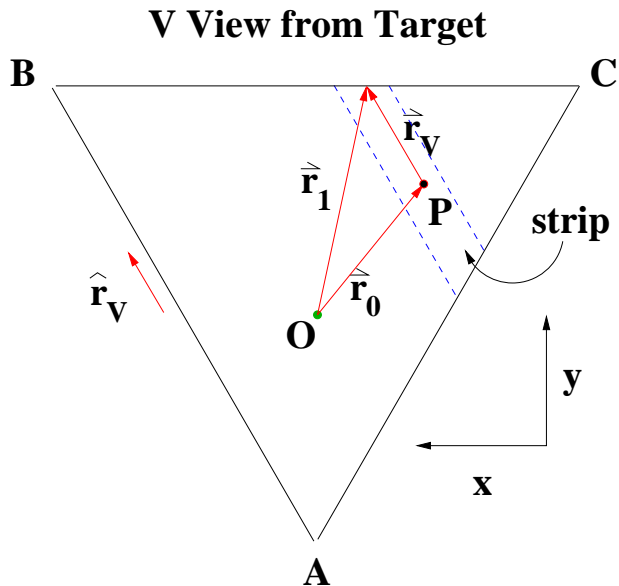
Figure 8: Front view of V layer showing quantities needed to calculate the photon attenuation of a hit at point P.

We want to get $\vec{r}_V$. The vector $\vec{r}_1$ can be written as

$$\vec{r}_1 = \vec{r}_0 + l\hat{r}_V \tag{34}$$

where

$$\hat{r}_V = \frac{\vec{B} - \vec{A}}{|\vec{B} - \vec{A}|} \qquad . \tag{35}$$

We can now set $y_{BC} = pDy_1$ and solve for l to obtain $\vec{r}_V$. Once we have accounted for the photon attenuation we calculate the expected PMT gain using (10 channels/MeV) and smear with the PMT resolution using parameters from the CLAS6 GSIM simulation. We also calculate the expected TDC signal using 20 ns/channel.

5   EC Simulation Tests and Results

We now show some initial results for the gemc simulation of the EC. Figure 9 shows the CLAS12 detector including the forward electromagnetic calorimeter in the left-hand panel and the same view of CLAS12 with a single electron event in the EC in the right-hand panel.

   To test the accuracy of the geometry of the simulation we simulated straight tracks. We used the geometry model described in Section 3 to predict θ and ϕ for a track that goes in a straight line from the CLAS12 origin to the three vertices of the first scintillator layer and the three vertices of the last scintillator layer. We then simulated a 'geantino' with the magnetic field turned off. The geantino is a special particle in Geant4 that does not deposit energy in any Geant4 volume, but otherwise behaves as an existing particle would. This
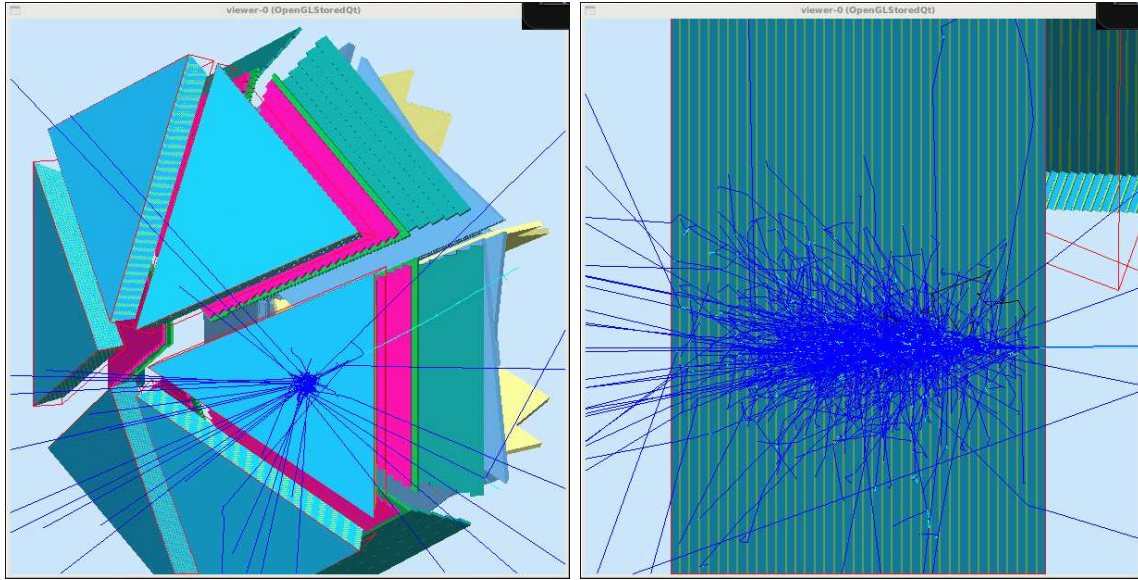
Figure 9: The CLAS12 detector in gemc including the EC (left-hand panel) and with an electron event (right-hand panel). Blue tracks are photons; light blue/cyan are electrons; black are neutrons.

test probes the consistency of EC geometry model and its implementation in gemc. Sample results are shown in Figure 10.

To test the *gemc* simulation of the electromagnetic calorimeter we have extracted a number of quantities and compared them with past simulation and measurement results from CLAS6. The first test is extracting the EC sampling fraction, *i.e.* the ratio of energy measured in the EC to the expected value. The results of a GSIM simulation of the CLAS6 are reproduced from Ref. [1] in the right-hand panel of Figure 11. The black curve in the right-hand panel is a CLAS6 calculation of the EC sampling fraction based on ionization energy loss in materials preceding the EC in CLAS6. The GSIM simulation agrees with the calculation for $p_e > 1.5$ GeV, but the CLAS6 calculation overpredicts the sampling fraction at low electron momentum. To determine the sampling fraction from the *gemc* simulation we used the following method. (1) A beam of mono-energetic electrons was incident on the face of the EC at right angles. The magnetic field was turned off to make the results simpler to interpret, ı.e. there are no edge effects or tracks striking the EC face at shallow angles. (2) A histogram of the deposited energy in the EC was formed. We chose not to use the results of tracking (and the magnetic field was turned off) to establish a baseline using only the simulated hit information. In the future we will consider the results of tracking. The total energy deposited was determined by taking the product of the number of counts in each bin with the value of the deposited energy at the bin center and then adding this product for all bins. (3) The results in part 2 was then divided by the known energy of the incident electrons. The results of this analysis for a range of different, incident momenta are shown in the left-hand panel of Fig. 11. The black curve is the same CLAS6 calculation drawn on the right-hand panel. The red points show the sampling fraction extracted in this manner with a lower limit of $E_{dep} > 0$ on the deposited energy. This threshold removes any
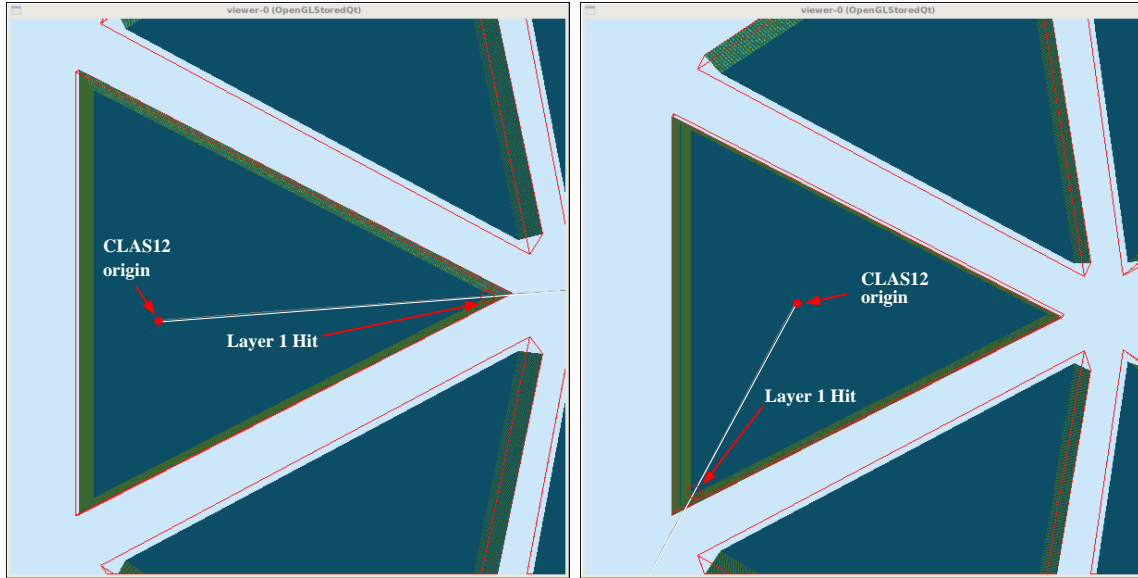
Figure 10: An example of the straight tracks used to test EC geometry (layer 1, inner vertex) is shown (left-hand panel). The test for layer 1, 'top-left' vertex is shown in the right-hand panel.

hits that do not deposit energy in that volume of the EC and would not register a signal in an actual measurement. The blue points show the sampling fraction for events where this threshold on the deposited energy was raised to 1 MeV. The zero-threshold points in red are 1-2% below the calculation at high-momenta, but have qualitatively different behavior near zero. In this region, the sampling fraction from the *gemc* simulation increases which disagrees with the CLAS6 calculated sampling fraction and the CLAS6 GSIM results in the right-hand panel. Applying even a low threshold of 1 MeV to the deposited energy (blue points) drastically changes the *gemc* simulation at low momentum. The blue points turn over and the sampling fraction decreases at low momentum like the calculation and the CLAS6 GSIM simulation. The *gemc* simulation is 1-2% below the calculated sampling fraction. This agreement between the *gemc* simulation and the CLAS6 results is good considering the differences in methods. The materials the electrons pass through before reaching the EC are similar, but not exactly the same. Straight tracks were used in the *gemc* simulation while the CLAS6 magnetic field was turned on for the GSIM simulation. Finally, tracking was used in the GSIM simulation while for the *gemc* calculation we relied on the deposited energy signal known in the *gemc* simulation.

The second test of the *gemc* simulation was to compare the energy resolution with previous results. We determined the *gemc* resolution from the width of the sampling fraction for mono-energetic electrons striking the EC at 90° to the front face of the calorimeter. In the right-hand panel of Fig. 12 we reproduce a plot from Ref. [1] showing the CLAS6 resolution calculated with GSIM. Here, the resolution was determined (like the CLAS6 sampling fraction above) for events that were reconstructed after passing through the CLAS6 magnetic field and the other components of CLAS6 that lie in front of the EC. Previous studies of the
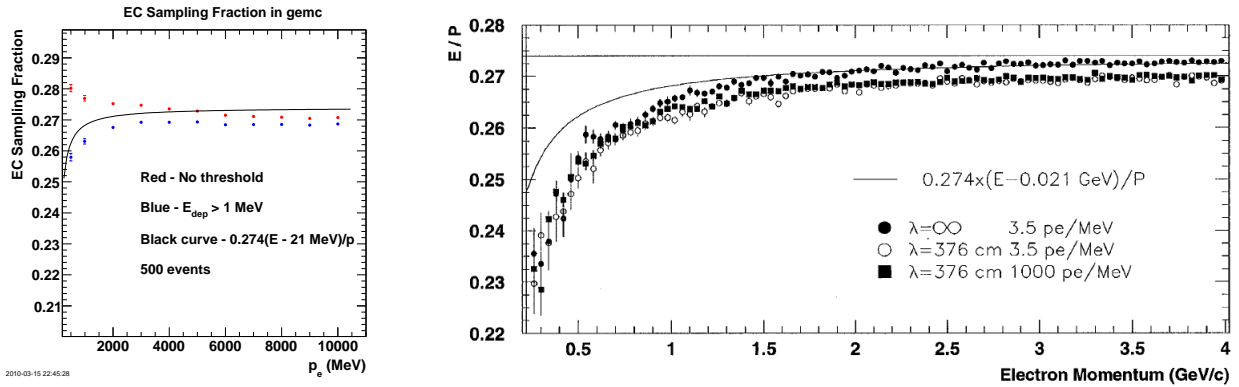
Figure 11: The sampling fraction for the EC in CLAS12 and CLAS6 is shown. The points in the right-hand panel are the CLAS6 results from Ref. [1] using the GSIM simulation. The points in the left-hand panel are the CLAS12 results using the *gemc* simulation. The black curve in each plot is based on ionization energy loss in materials preceding the EC in CLAS6. Note different horizontal ranges.
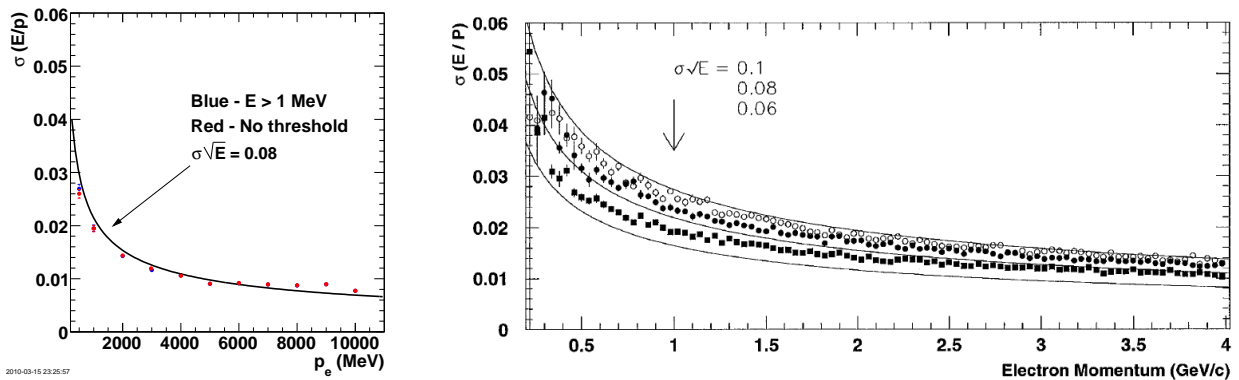
Figure 12: The resolution extracted from *gemc* (left-hand panel) and from the CLAS6 GSIM (right-hand panel from Ref. [1]. Note different horizontal ranges.

EC revealed the resolution varied as $\sigma/E = a/\sqrt{E}$ where the parameter a varies over the range $a = 0.085 - 0.095$ [7]. The three curves in the right-hand panel bracket this range. The different points on the plot are for different choices of the light attenuation parameters in the GSIM simulation. The *gemc* results for the resolution study are shown in the left-hand panel of Fig. 12. The width of the sampling fraction peak at each electron momentum is independent of the choice of threshold (the red points mostly sit on top of the blue ones). The *gemc*-based resolution is larger at low momentum and drops to $\approx 1\%$ at momenta above $p_e = 5$ GeV/c. It largely agrees with the CLAS6 parameterization of the resolution based on GSIM and represented by the middle curve in the right-hand panel of Fig. 12.

The last property we studied with the *gemc* simulation is the transverse shower size in the electromagnetic calorimeter. This quantity is a measure of the spatial resolution of the EC and linking the position of a particle in the EC with the track measured with the drift chambers is an essential part of the track reconstruction. The expectation for the CLAS6 shower size is based on the CLAS6 GSIM simulations in Refs. [1]-[7]. It was found in that

work that 95% of the energy of the shower was contained within a 4 cm transverse diameter[7]. The algorithm for determining the position of a hit in the CLAS6 EC is described in Ref. [1]. For the *gemc* simulation here we again relied on the deposited energy information. Mono-energetic, incident electrons were directed at a point on the face of the EC and in a direction perpendicular to the face. In *gemc* a set of local coordinates are used where the x and y components lie in the face of the EC and the z component is perpendicular. The origin lies along the line bisecting the face of the EC and passing through the apex of the EC triangle closest to the beamline. A histogram of the energy deposited in the EC as a function of the transverse distance in the x direction is shown in the left-hand panel of Fig. 13 There is a
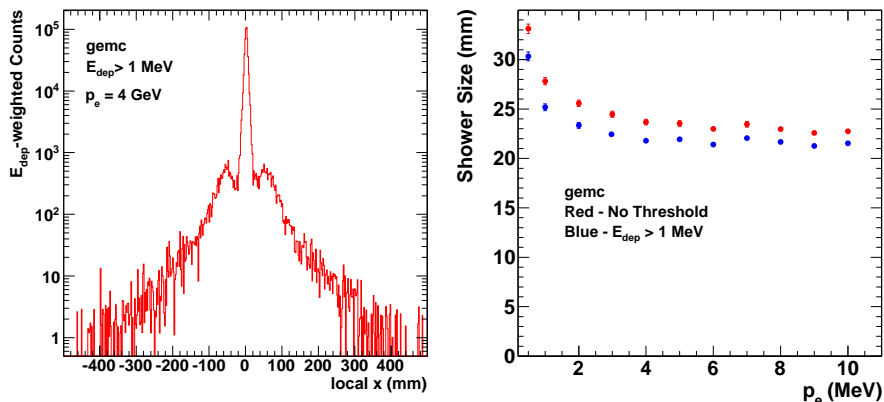
Figure 13: Results of *gemc*-based study of the shower size for electrons in the EC. The CLAS6 shower size is $\approx$ 4 cm diameter for 2.4 GeV electron (*e.g.* 95% of shower energy contained within 2 cm of centroid [1].

sharp peak at $x = 0$ in the local coordinates as expected and two smaller peaks at $\approx \pm 7$ cm. The central peak is due to the electrons striking the center of the EC. The side peaks appear from a combination of the width of the shower, the size of the strips which is 7 cm, and the triangular shape of the pixels in the EC created by the crossed strips that form the U, V, and W views. The shower is wide enough that some of the particles will strike strips next to the center one. The pixels in the EC form horizontal rows of triangles with the vertex of each triangle at the top or bottom. Even with a uniform distribution of events peaks would appear when the distribution for one row is projected down onto the local x axis. There is more area to project down the center of the triangle than on the edges. The area will increase as you go from left to right until you reach the apex of each triangular pixel and then the area will go down again. The area of these strips multiplied by the average occupancy (number of events) on each strip will give you the projection of the number of events along the horizontal (i.e. x) axis. Even a uniform distribution then will have a peak in the middle. To test this distribution we integrated the distribution in the left-hand panel of Fig. 13 over the range $x = \pm 20$ mm and divided by the integral over the full range of x. In the CLAS6, GSIM simulation 95% of the energy of the shower would lie with 2 cm. We found here that we could reproduce that result by raising the threshold on the deposited energy E_{dep} up to about 5 MeV. The last test we applied to the distribution in the left-hand

panel of Fig. 13 is to measure the width of the central peak. The dependence of this width on the incident electron energy is shown in the right-hand panel. The red points show the width as a function of the incident electron momentum when the threshold on the deposited energy was $E_{dep} > 0$ MeV. The blue points show the width when a threshold of 1 MeV was applied. There is a modest improvement in the resolution with the higher threshold. Both distributions have greater widths at low momentum which drop down to about 22 mm at higher momentum. We find satisfactory agreement between the *gemc* results and previous CLAS6 simulations using GSIM even though different methods were used in the two different studies. We used the deposited energy distributions while the CLAS6 studies relied on a more complete reconstruction algorithm for the EC analysis.

6   Summary

In this CLAS-NOTE we describe the implementation of the CLAS12 electromagnetic calorimeter in the physics-based simulation of the detector called *gemc*. We provide a short description of the workings of the EC and a streamlined version of the geometry that builds on previous work of Minehart [5]. To incorporate the EC into *gemc* we use the Geant4 package from CERN to calculate the passage of radiation through the CLAS12 volumes. Each scintillator layer of the EC is treated in the geometry as a large, continuous piece of material. The strips that make up the actual detector are constructed in the digitization stage. We have applied a variety of tests to check the consistency of the work. A special particle type in Geant4 called a geantino was used to check the positions of the vertices of the triangular layers in the EC. We also extracted from the simulation the sampling fraction, the energy resolution, and shower size and compared these quantities with ones studied in the CLAS6 GSIM simulation. In each case there was satisfactory agreement between the CLAS12 and CLAS6 results.

References

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[7] Demirchyan R. Geant simulation of CLAS forward calorimeter performance. CLAS-Note 1993-009, Jefferson Lab, 1993.

A   Lead Sheet Dimensions

The lead sheets are on the average 2.387 mm thick. They are cut to cover the active triangular area as well as the extension on the light collection side of the layer defined by the length d_2. Layers 4,7,10 etc. have the vertex at the beam side clipped off. Their dimensions do not follow a simple formula. On average, the z coordinate of the front surface of each layer of lead is 100.0 mm greater than the z coordinate of the front surface of the preceding layer of scintillator. In the following table layer 2 of the lead is between scintillator 1 and 2, etc. There is no layer 1 of lead. Measurements are from [5].

Layer	Base	Height	Truncation	Layer	Base	Height	Truncation
2	152.096	147.264	0	21	158.527	154.821	0
3	152.454	148.890	0	22	158.975	155.258	1.00
4	152.948	149.372	1.440	23	159.246	155.523	0
5	153.174	149.636	0	24	159.605	155.873	0
6	153.532	149.943	0	25	160.054	156.311	1.00
7	154.033	150.433	1.448	26	160.324	156.575	0
8	154.252	150.007	0	27	160.683	156.926	0
9	154.610	150.996	0	28	161.130	157.363	1.00
10	155.118	151.492	1.455	29	161.400	157.628	0
11	155.328	151.379	0	30	161.760	157.979	0
12	155.688	152.048	0	31	162.208	158.415	1.00
13	156.203	152.552	1.462	32	162.478	158.681	0
14	156.406	152.750	0	33	162.838	159.032	0
15	156.766	153.101	0	34	163.286	159.468	1.00
16	156.820	153.153	1.00	35	163.556	159.733	0
17	157.090	153.417	0	36	163.916	160.084	0
18	157.449	153.768	0	37	164.364	160.521	1.00
19	157.898	152.206	1.00	38	164.634	160.786	0
20	158.168	154.470	0	39	164.994	161.137	0

B   Walls of the Containment Box

The side walls of the containment box can be represented by six planes of 1.5"thick aluminum. The vertices of the planes can be represented by 12 points at the rear of the box, six for the outside and six for the insides surfaces. The labeling of these points is indicated in the figure. The coordinates of the points in the local detector frame are shown in the next table. Measurements are from [5].

P1	2079.19	2076.73	0.	P7	2259.10	2255.70	480.72
P2	-2079.19	2076.73	0.	P8	-2259.10	2255.70	480.72
P3	-2139.49	1959.89	0.	P9	-2319.43	2138.86	480.72
P4	-65.02	-2092.05	0.	P10	-65.02	-2264.50	480.72
P5	65.02	-2092.05	0.	P11	65.02	-2264.50	480.72
P6	2139.49	1959.89	0.	P12	2319.43	2138.86	480.72
P1'	2043.41	2036.06	0.	P7'	2223.31	2215.06	480.72
P2'	-2043.41	2036.09	0.	P8'	-2223.31	2215.06	480.72
P3'	-2089.43	1946.89	0.	P9'	-2269.36	2125.85	480.72
P4'	-42.34	-2051.61	0.	P10'	-42.34	-2224.05	480.72
P5'	42.34	-2051.61	0.	P11'	42.34	-2224.05	480.72
P6'	2089.43	1946.89	0.	P12'	2269.36	2125.85	480.72

The six surfaces can be characterized by the following outward pointing normal vectors:

n_1	0	$\cos(20.42)$	$-\sin(20.42)$
n_2	0.87848	-0.44975	-0.161259
n_3	-0.87848	-0.44975	-0.161259
n_4	0.79367	0.40978	-0.44693
n_5	-0.79367	0.40978	-0.44693
n_6	0	-0.94217	-0.33765

C   Perl script for generating EC geometry

```
#!/usr/bin/perl -w
#
# Perl sctipt used to generate a file (EC.txt) that is an input to
# the shell script go_table which. puts the EC geometry in the mysql
# database for gemc to use. Modified from original by C.Musalo 7/16/10
# load libraries

#use strict;
use lib ("$ENV{GEMC}/database_io");
use geo;
use geo qw($pi);
use Getopt::Long;
use Math::Trig;

# local quantities.

my $envelope = 'EC';
my $file     = 'EC.txt';
my $rmin = 1;
my $rmax = 1000000;
#
# parameters first. These are described in CLAS-Note 2010-?? by Gilfoyle et al.
#
# Face of the EC is tilted 25 degrees, the large angle side is rotated towards detector,
# and the small angle vertex is rotated away from detector.
#
#  large angle side(top) -->  /\
#                            \ \
#       Side view             \ \
#                              \ \
#                               \ \
#                                \_\   <-- small angle vertex(bottom)
#  target  |
#
# We are using the Hall B coordinate system with the origin at the target center.

$thetaEC_deg = 25.0;                    # angle of EC face to a line perpendicular to the beamline.
$thetaEC = $thetaEC_deg*$pi/180;        # angle of EC face to a line perpendicular to the beamline in radians.
$theta0 = 62.889041*$pi/180;            # angle between sides of EC at large scattering angle (angles opposite the beamside vertex) in radians.
$a1 = 0.08555;                          # see CLAS-Note 2010-
$a2 = 1864.65;
#$a3 = 4.627;   # corrected 10/3/10
```

```
$a3 = 4.45635;
#$a4 = 4.3708;                        # Used to get the position of the u strips.
#$a5 = 103.66;                        # Used to get the width of the u strips.
#$a6 = 0.2476;                        # Used to get the width of the u strips.
#$a7 = 94.701;                        # Used to get the width of the v strips.
#$a8 = 0.2256;                        # Used to get the width of the v and w strip;
#$a9 = 94.926;                        # Used to get the width of the w strips.

$dlead = 2.381;                       # thickness of lead layers in mm.
$dscint= 10.0;                        # thickness of scintillator layers in mm.
$nlayers = 39;                        # number of scintillator layers, there are 38 lead layers (no lead layer 1).
$L1 = 7217.23;                        # length of line perpendicular to EC face that passes through the CLAS12 target.
$ypo = 950.88;                        # distance from perpendicular point to the geometric center of the front face of the first scintillator.
$MUoffset = 5000.0;                   # the CLAS12 target is at +5m (or -2 m??) in the gemc coordinates.

#derived quantities.

$tantheta = tan($theta0);             # tangent of angle between sides of EC at large scattering angle (angles opposite the beamside vertex).
$gamma1 = $pi - 2*$theta0;            # angle between sides of EC at small scattering angle.
$totaldepth = ($nlayers-1)*($dscint+$dlead) + $dscint; # total thickness of lead and scintillator. There are 39 scintillator layers and 38 lead layers.

my %detector = ();    # hash (map) that defines the gemc detector
$detector{"rmin"} = $rmin;
$detector{"rmax"} = $rmax;

# Mother Volume - description of parameters for Geant4 G4Trap volume.
#
# pDx1    Half x length of the side at y=-pDy1 of the face at -pDz
# pDx2    Half x length of the side at y=+pDy1 of the face at -pDz
# pDz     Half z length
# pTheta  Polar angle of the line joining the centres of the faces at -/+pDz
# pPhimom Azimuthal angle of the line joining the centre of the face at -pDz to the centre of the face at +pDz
# pDy1    Half y length at -pDz
# pDy2    Half y length at +pDz
# pDx3    Half x length of the side at y=-pDy2 of the face at +pDz
# pDx4    Half x length of the side at y=+pDy2 of the face at +pDz
# pAlp1   Angle with respect to the y axis from the centre of the side (lower endcap)
# pAlp2   Angle with respect to the y axis from the centre of the side (upper endcap)
#
# Note on pAlph1/2: the two angles have to be the same due to the planarity condition.
#
# all numbers are in mm or deg as specified in the $detector{"dimensions"} statement.

my $pDzmom    = $totaldepth/2.0;                      # half z length
my $pDy1mom   = &sycenter($nlayers) + &spDy($nlayers);  # maximum half y length at -pDz.
my $pDy2mom   = $pDy1mom;                              # half y length at +pDz.
my $pDx1mom   = 0.001;          # should be zero, but that makes gemc crash.
my $pDx2mom   = &spDx2($nlayers); # Half x length of the side at y=+pDy1 of the face at -pDz.
my $pThetamom = 0;              # Polar angle of the line joining the centres of the faces at +/-pDz
my $pPhimom   = $pThetamom;     # Azimuthal angle from the centre of the face at -pDz to the centre of the face at +pDz.
my $pDx3mom   = $pDx1mom;        # half x length of the side at y=-pDy2 of the face at +pDz
my $pDx4mom   = $pDx2mom;        # Half x length of the side at y=+pDy2 of the face at +pDz
my $pAlp1mom  = $pThetamom;      # angle with respect to y axis from centre of side(lower endcap)
my $pAlp2mom  = $pThetamom;      # angle with respect to y axis from centre of side(uppder endcap)

# Geant4 builds mother volume in one sector, than rotates the contents in the
# 1st sector to form 6 total sectors. Sector orientations shown below looking
# in the direction of the beam.
#
#            TOP                    ^  y
#             .                     |
#          .  .  .                  |
#       .     .     .       x <----
#    .        .        .
# .       2   .   3        .
# .   .       .       .   .
# .       .   .   .       .
# .   .       .       .   .
# .   1       .       4   . z/beam - into page
# .       .   .   .       .
# .   .       .       .   .
# .       .   .   .       .
# .       6   .   5        .
#    .        .        .
#       .     .     .
#          .  .  .
#             .

# We place the origin at the geometric center of each layer. The z axis runs along the beam line,
# the y axis points vertically straight up from beam line and the x axis points left looking out along
# the beam line. Calculate the position of the center of first scintillator face as the origin.
#
#     1. Get the vector from the target center to the front face of the first scintillator and perpendicular to the face.
my@L1vec = ( 0, $L1*sin($thetaEC), $L1*cos($thetaEC));
#     2. Vector that takes you from perpendicular point at L1vec to geometric center of Clas12 EC layer 1.
my@Svec = ( 0,-$ypo*cos($thetaEC), $ypo*sin($thetaEC));
#     3. Now add L1vec+Svec.
my@CLAS12front = ($L1vec[0]+ $Svec[0], $L1vec[1]+ $Svec[1], $L1vec[2]+ $Svec[2]);
#     4. Get vector from center of front face to the midpoint in the z direction
my@toCenter = (0, $totaldepth*sin($thetaEC),$totaldepth*cos($thetaEC));
#     5. Get final vector from target to center of the mother volume with origin at the center of the front face.
#        MUoffset is needed since the target is at z = 5000 mm and not at the origin.
```

```
my@CLAS12center = ($CLAS12front[0]+$toCenter[0],$CLAS12front[1]+$toCenter[1],$CLAS12front[2]+$toCenter[2]-$MUoffset);

# array used to calculate pdX values for Geant4. Some lead layers are truncated at the small angle vertex.
@beamVertexCut=(0.00001, 0.0000001, 1.440, 0.0000001, 0.000001, 1.448, 0.000001, 0.000001, 1.455, 0.001,
    0.000001, 1.462, 0.000001, 0.000001, 1.0, 0.000001, 0.00001, 1.0, 0.000001, 0.000001, 1.0, 0.000001, 0.000001,
    1.0, 0.000001, 0.000001, 1.0, 0.001, 0.000001, 1.0, 0.000001, 0.000001, 1.0, 0.000001, 0.000001);

# generate red mother volume wireframe box, and write to a file.
$detector{"name"}        = "EC";
$detector{"mother"}      = "sector";
$detector{"description"} = "Forward Calorimeter";
$detector{"pos"}         = "${CLAS12center[0]}*mm ${CLAS12center[1]}*mm ${CLAS12center[2]}*mm";
$detector{"rotation"}    = "$thetaEC_deg*deg 0*deg";# pure rotation about the geometric center of EC mother volume.
$detector{"color"}       = "ff1111";
$detector{"type"}        = "G4Trap";
$detector{"dimensions"}  = "${pDzmom}*mm ${pThetamom}*deg ${pPhimom}*deg ${pDy1mom}*mm ${pDx1mom}*mm ${pDx2mom}*mm ${pAlp1mom}*deg
                            ${pDy2mom}*mm ${pDx3mom}*mm ${pDx4mom}*mm ${pAlp2mom}*deg";
$detector{"material"}    = "Air";
$detector{"mfield"}      = "no";
$detector{"ncopy"}       = 1;
$detector{"pMany"}       = 1;
$detector{"exist"}       = 1;
$detector{"visible"}     = 1;
$detector{"style"}       = 0;
$detector{"sensitivity"} = "no";
$detector{"hit_type"}    = "";
$detector{"identifiers"} = "";

#print "\nStreamlined Results: \n\n";
#print "pDzmom=",$pDzmom," pThetamom=",$pThetamom," pPhimom=",$pPhimom," pDy1mom=",$pDy1mom," pDy2mom=",$pDy2mom,"\n";
#print "pDx1mom=",$pDx1mom," pDx2mom=",$pDx2mom," pDx3mom=",$pDx3mom," pDx4mom=",$pDx4mom," pAlp1mom=",$pAlp1mom," pAlp2mom=",$pAlp2mom,"\n\n";

print_det(\%detector, $file);

# now start to do the alternating layers of scintillator and lead. Set up inputs first.

# All volumes produced are now placed in mother volume's coordinate sytem.
# The Mother volume coordinate system has it's y axis running from the mother
#  volumes small angle vertex straight up to form a perpendicular angle at the
#  midpoint of the large angle side.
#
#
#              large angle side(top).
#        ...........................
#       \          |          /
#       .          |          .
#       \          |          /
#      .           |           .
#       \          |y_axis    /
#      .           |           .
#        \         |         /
#       .          |          .
#         \        |        /
#      _____ o_____x_axis____
#          \        |       /
#         .         |        .
#          \        |       /
#           .       |      .
#            \      |     /
#            .      |      .
#             \     |    /
#              .    |   .
#               \   |  /
#               .   |  .
#                \  | /
#                .  | .
#                 \ |/
#                 . | .
#                  \|/
#                   .
#           small angle vertex(bottom)
#
my $subname;
my $submother = "EC";;
my $description;
my $pos;
my $rotation = "0*deg 0*deg 0*deg";
my $color = "0147FA";
my $type = "G4Trap";
my $dimensions;
my $material ="Air";
my $mfield = "no";
my $ncopy = 1;
my $pMany = 1;
my $exist = 1;
my $visible = 1;
my $style = 1;
my $sensitivity = "no";
my $hit_type = "";
my $identifiers = "";

# a scintillator layer first. set the G4Trap parameters.
```

```
#
my $pDx1    = 0.001;  # should be zero, but that makes gemc crash.
my $pDx2    = &spDx2(1);
my $pDz     = $dscint/2.0;   #<------------------------------------
my $pTheta = 0;
my $pPhi   = $pTheta;
my $pDy1   = &spDy(1);
my $pDy2   = $pDy1;
my $pDx3   = $pDx1;
my $pDx4   = $pDx2;
my $pAlp1  = $pTheta;
my $pAlp2  = $pTheta;

my $i = 1;
my $view   = &ECview($i);
my $stack  = &ECstack($i);

# fill the Geant4 description of the volume and write the results into the file.

my $xscint = &sxcenter($i);
my $yscint = &sycenter($i);
my $zscint = &szcenter($i);

$subname = "EClayerScint${i}";
$description ="Forward Calorimeter scintillator layer ${i}";
$pos = "$xscint*mm $yscint*mm $zscint*mm";
$detector{"name"}         = $subname;
$detector{"mother"}       = "EC";
$detector{"description"} = $description;
$detector{"pos"}          = $pos;
$detector{"rotation"}     = $rotation;
$detector{"color"}        = "0147FA";
$detector{"type"}         = "G4Trap";
$detector{"dimensions"}  = "${pDz}*mm ${pTheta}*deg ${pPhi}*deg ${pDy1}*mm ${pDx1}*mm ${pDx2}*mm ${pAlp1}*deg ${pDy2}*mm
                            ${pDx3}*mm  ${pDx4}*mm  ${pAlp2}*deg";
$detector{"material"}     = "Scintillator";
$detector{"mfield"}       = "no";
$detector{"ncopy"}        = 1;
$detector{"pMany"}        = 1;
$detector{"exist"}        = 1;
$detector{"visible"}      = 1;
$detector{"style"}        = 1;
$detector{"sensitivity"} = "EC";
$detector{"hit_type"}    = "EC";
$detector{"identifiers"} = "sector ncopy 0 stack manual $stack view manual $view strip manual 36";

#print "\nStreamlined Results for scint 1: \n\n";
#print "pDz=",$pDz," pTheta=",$pTheta," pPhi=",$pPhi," pDy1=",$pDy1," pDy2=",$pDy2,"\n";
#print "pDx1=",$pDx1," pDx2=",$pDx2," pDx3=",$pDx3," pDx4=",$pDx4," pAlp1=",$pAlp1," pAlp2=",$pAlp2,"\n\n";


print_det(\%detector, $file);

#for loop loops over layers and generates Geant4 parameters for each scint and lead layer.

for ($i = 2; $i <= $nlayers; $i++) {

# lead layer

    my $xlead = &sxcenterPb(${i});
    my $ylead = &sycenterPb(${i});
    my $zlead = &szcenterPb(${i});

    $subname = "EClayerLead${i}";
    $description = "Forward Calorimeter lead layer ${i}";
    $pos = "${xlead}*mm ${ylead}*mm ${zlead}*mm";          #position of center of trapezoid.
    $pDz = $dlead/2.0;
    $pDy1 = &spDy($i) - $beamVertexCut[$i-2];
    $pDy2 = $pDy1;
    $pDx1 = $beamVertexCut[$i-2]*tan($gamma1/2);
    $pDx3 = $pDx1;
    $pDx2 = &spDx2($i);
    $pDx4 = $pDx2;
    $pTheta = 0;
    $pPhi   = $pTheta;
    $pAlp1  = $pTheta;
    $pAlp2  = $pTheta;
    $detector{"name"}         = $subname;
    $detector{"mother"}       = $submother;
    $detector{"description"} = $description;
    $detector{"pos"}          = $pos;
    $detector{"rotation"}     = $rotation;
    $detector{"color"}        = "7CFC00";
    $detector{"type"}         = "G4Trap";
    $detector{"dimensions"}  = "${pDz}*mm ${pTheta}*deg ${pPhi}*deg ${pDy1}*mm ${pDx1}*mm  ${pDx2}*mm  ${pAlp1}*deg
                                ${pDy2}*mm ${pDx3}*mm  ${pDx4}*mm  ${pAlp2}*deg";
    $detector{"material"}     = "Lead";
    $detector{"mfield"}       = "no";
    $detector{"ncopy"}        = 1;
    $detector{"pMany"}        = 1;
    $detector{"exist"}        = 1;
    $detector{"visible"}      = 1;
```

```
    $detector{"style"}       = 1;
    $detector{"sensitivity"} = "no";
    $detector{"hit_type"}    = "";
    $detector{"identifiers"} = "";
#write values to a file.
    print_det(\%detector, $file);


# scintillator layer

    $xscint = &sxcenter($i);
    $yscint = &sycenter($i);
    $zscint = &szcenter($i);

    $subname = "EClayerScint${i}";
    $description ="Forward Calorimeter scintillator layer ${i}";
    $pos = "${xscint}*mm ${yscint}*mm ${zscint}*mm";
    $pDz = $dscint/2.0;
    $pDy1 = &spDy($i);
    $pDy2 = $pDy1;
    $pDx1 = 0.001;
    $pDx3 = $pDx1;
    $pDx2 = &spDx2($i);
    $pDx4 = $pDx2;
    $pTheta = 0;
    $pPhi   = $pTheta;
    $pAlp1  = $pTheta;
    $pAlp2  = $pTheta;
    $detector{"name"}        = $subname;
    $detector{"mother"}      = $submother;
    $detector{"description"} = $description;
    $detector{"pos"}         = $pos;
    $detector{"rotation"}    = $rotation;
    $detector{"color"}       = "0147FA";
    $detector{"type"}        = "G4Trap";
    $detector{"dimensions"}  = "${pDz}*mm ${pTheta}*deg ${pPhi}*deg  ${pDy1}*mm ${pDx1}*mm  ${pDx2}*mm  ${pAlp1}*deg  ${pDy2}*mm
                               ${pDx3}*mm  ${pDx4}*mm  ${pAlp2}*deg";
    $detector{"material"}    = "Scintillator";
    $detector{"mfield"}      = "no";
    $detector{"ncopy"}       = 1;
    $detector{"pMany"}       = 1;
    $detector{"exist"}       = 1;
    $detector{"visible"}     = 1;
    $detector{"style"}       = 1;
    $detector{"sensitivity"} = "EC";
    $detector{"hit_type"}    = "EC";

    $view = &ECview($i);
    $stack= &ECstack($i);
    $detector{"identifiers"} = "sector ncopy 0 stack manual $stack view manual $view strip manual 36";

    if ($i == 1) {
       print "\nStreamlined Results for scint ",$i,": \n\n";
       print "pDz=",$pDz," pTheta=",$pTheta," pPhi=",$pPhi," pDy1=",$pDy1," pDy2=",$pDy2,"\n";
       print "pDx1=",$pDx1," pDx2=",$pDx2," pDx3=",$pDx3," pDx4=",$pDx4," pAlp1=",$pAlp1," pAlp2=",$pAlp2,"\n";
       print "xscint=",$xscint," yscint=",$yscint,"  zscint=",$zscint,"\n\n";
    }

    print_det(\%detector, $file);

  }
#
#subroutines *********************************************************************
#
# scintillator positions:
# gives the x position of each scintillator layers geometric center inside the mother volume.
sub sxcenter($){
    my $xcent = 0;
    return $xcent;
}
#gives the y position of each scintillator layers geometric center inside the mother volume.
sub sycenter($){
    my $ycent = $a1*($_[0] - 1);
    return $ycent;
}
#gives the z position of each scintillator layers geometric center inside the mother volume.
sub szcenter($){
    my $layer = $_[0];
    my $zcent = -$totaldepth/2 + ($layer - 1)*($dscint + $dlead) + $dscint/2;
    return $zcent;
}

# lead positions.
#gives the x position of each lead layers geometric center inside the mother volume.
sub sxcenterPb($){
    my $xcentPb = 0;
    return $xcentPb;
}
#gives the y position of each lead layers geometric center inside the mother volume.
sub sycenterPb($){
    my $ycentPb = &sycenter($_[0]) + $beamVertexCut[$_[0]-2]/2;
    return $ycentPb;
}
```

```perl
#gives the z position of each lead layers geometric center inside the mother volume.
sub szcenterPb($){
    my $zcentPb = -$totaldepth/2 + ($_[0] - 2)*($dscint + $dlead) + $dscint/2 + ($dscint+$dlead)/2;
    return $zcentPb;
}


# half-widths of lead and scintillator layers.
#
# gives half y distance of trapezoidal EC layer $i,
sub spDy($){
    my $ywidth = $a2 + $a3*($_[0] - 1);
    return $ywidth;
}
# gives half x distance of trapezoidal EC layer $i;
sub spDx2($){
    my $xwidth = (2*&spDy($_[0]))/($tantheta);
    return $xwidth;
}




sub ECview($) {
    # using the layer to generate a number (1,2,3) for the different views (U, V,W).

    my $layer = $_[0];
    my $mod = $layer%3;

    my $view = 4;
    if ($mod == 1) {$view = 1;}
    if ($mod == 2) {$view = 2;}
    if ($mod == 0) {$view = 3;}

    if ($view == 4) {print "**** WARNING: No View assignment made. ****\n";}

    return $view;

}

sub ECstack($) {
    # using the layer to generate a number (1,2,3) for the inner and outer stacks in the EC.

    my $layer = $_[0];

    my $stack = 3;
    if ($i <= 15) {$stack = 1;}
    if ($i >  15) {$stack = 2;}
    if ($stack == 3) {print "**** WARNING: No Stack assignment made. ****\n";}

    return $stack;

}
```