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Implementation of the CLAS12 HTCC into GEMC

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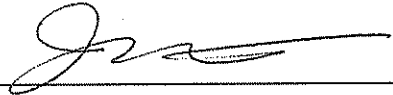at the

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APPROVAL PAGE

Master of Science Thesis

Implementation of the CLAS12 HTCC into GEMC

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Acknowledgments

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Implementation of the CLAS12 HTCC into GEMC

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I. INTRODUCTION

Experiments designed to probe the structure of the proton via electron-proton scattering date back to the 1960s when Hofstadter used a 188 MeV electron beam and hydrogen target to demonstrate the finite size of the proton. At such low energies, however, a high resolution model of the proton could not be developed. Further electron scattering experiments over the past fifty years have continued to reveal new information about the structure of the proton, but they too have suffered from shortcomings preventing them from revealing fully the structure and internal dynamics of the proton.

The Continuous Electron Beam Accelerator Facility's (CEBAF) Large Acceptance Spectrometer (CLAS) at Jefferson Lab in Newport News, VA is currently undergoing an upgrade that will, among other things, involve an increase in beam energy from 6 GeV to 12 GeV. This upgraded detector is known as CLAS12. CLAS12 will have the technology to make measurements of both semi-exclusive as well as fully exclusive processes, allowing for the studies of the proton's flavor structure and internal dynamics, respectively. The capacity to do this allows for measurements of deeply exclusive scattering processes to be made which connect transverse and longitudinal information, from which a three-dimensional image of the proton can be constructed.

Accurate particle identification is essential to the success of CLAS12. One of the components of the detector that contributes to particle identification is the High Threshold Čerenkov Counter (HTCC). When a charged particle travels through a medium faster than light travels through that medium, radiation known as Čerenkov Radiation is emitted. The HTCC uses this principle to differentiate between electrons and charged -mesons.

For simulation purposes, a computer model of the HTCC was built using a software package called GEANT4 (GEometry ANd Tracking) and implemented into another software package called GEMC (GEANT4 Monte Carlo simulator). GEANT4 was developed at the European Organization for Nuclear Research (CERN) and is a toolkit for simulating particles as they pass through matter; GEMC then uses this toolkit to run Monte Carlo simulations. Detector geometries can be replicated in GEMC by using predefined three dimensional shapes (boxes, ellipses, cones, etc.), and then combining two or more shapes or subtracting one shape from

another. The geometry of the CLAS12 HTCC was designed by Dr. Youri Sharabian. The following is a summary of that geometry as well as a description of how it was implemented into GEMC.

II.   COORDINATE SYSTEMS

The coordinate systems used are all Cartesian. The absolute coordinate system is defined with the target at (x,y,z) = (0,0,0), the beam going in the +z direction, and the +y direction going straight up from the ground. Additionally, each shape created in GEANT4 has its own relative coordinate system (indicated with a prime symbol ($'$)) that initially corresponds to the absolute coordinate system, but can be shifted and rotated. Rotations around the x, y, and z axes are performed in that order, unless otherwise specified, and are always with respect to the relative coordinates. Positive angles correspond to clockwise rotations. When performing a subtraction, for example, shape1 - shape2, the coordinates of shape2 are with respect to shape1's relative coordinate system.

III.   THE FOUR MIRRORS

The HTCC has 12 identical sectors (2 for each sector of the detector), each occupying $30°$ in the ϕ direction (see figure 3). Each sector consists of four mirrors. Each mirror is a piece of an ellipsoid of rotation. The geometry of the four ellipses defining these ellipsoids is summarized in figure 1 and table 1. The ellipsoids are created by spinning the ellipses about their major axes.
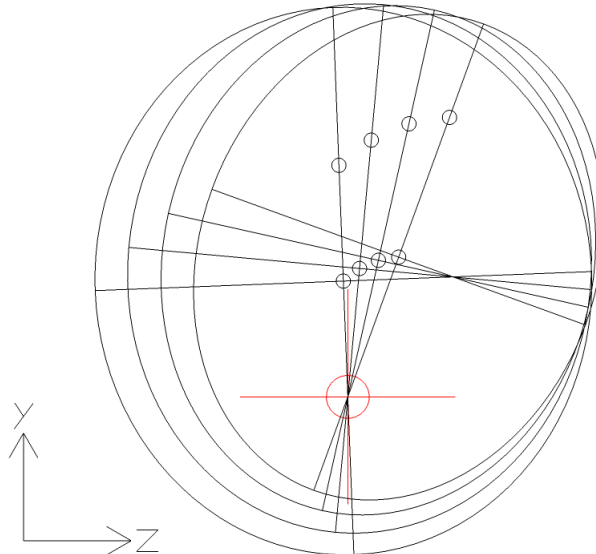
FIG.1: The four ellipses. The origin of the absolute coordinate system is indicated in red. The eight smaller circles indicate the positions of the ellipses' centers and focal points. All of the ellipses share a common focal point at the origin. Also shown are the major and minor axes of each ellipse.

Origin of relative system and angle rotated			
	x (mm)	y (mm)	z (mm)	γ (deg)
Mirror 1	0.0000	806.5149	-31.0234	2.2029
Mirror 2	0.0000	894.3460	81.6664	-5.2174
Mirror 3	0.0000	951.2034	212.7408	-12.6070
Mirror 4	0.0000	973.4736	353.8694	-19.9768

Ellipsoid semi-axis radii and focal point (other is at origin)					
	Rx (mm)	Ry (mm)	Rz (mm)	x (mm)	y (mm)	z (mm)
Mirror 1	1728.6727	1907.8098	1728.6727	0.0000	1613.0299	-62.0467
Mirror 2	1612.9985	1846.1550	1612.9985	0.0000	1788.6919	163.3327
Mirror 3	1497.6043	1786.8590	1497.6043	0.0000	1902.4068	425.4815
Mirror 4	1383.6210	1728.3754	1383.6210	0.0000	1946.9473	707.7389

Table 1: The values of all the parameters necessary to define the geometry of the four ellipsoids. See figure 1.

The HTCC uses the fact that when a signal leaves a focal point of an ellipse, that signal will be reflected directly to the other focal point. By putting the target at one focal point of each ellipse and a photomultiplier tube (PMT) at the other (to collect Čerenkov light), and by filling the surrounding volume with a Čerenkov Gas, particles with certain properties can be detected by the Čerenkov Light that they emit. The Čerenkov Light gets reflected off of the mirror and will then hit the corresponding PMT. The four aforementioned ellipsoids are each cut in such a way that each one forms a piece of the sector. The basic principle of the HTCC is illustrated in figure 2. Figure 3 shows the front view of the end result.
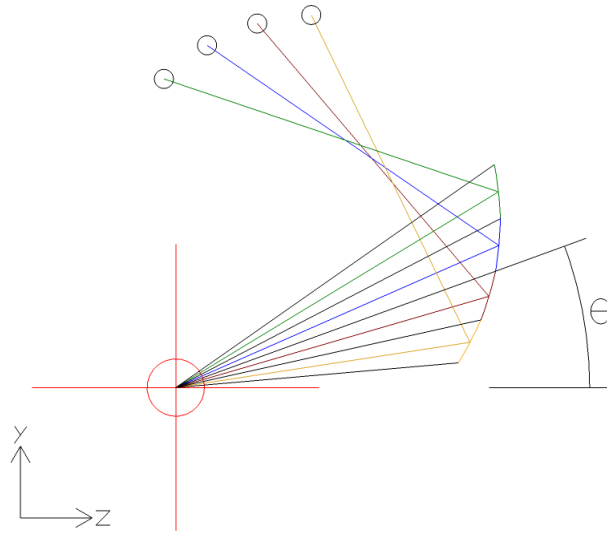

FIG. 2: A simplified drawing of how the HTCC works. The four colored curves are each a section of one of the four ellipses from figure 1. Mirror 1 is shown in green and occupies from

27.5° to 35° in the θ direction. Mirror 2 is shown in blue and occupies from 20° to 27.5° in the θ direction. Mirror 3 is shown in maroon and occupies from 12.5° to 20° in the θ direction. Mirror 4 is shown in goldenrod and occupies from 5° to 12.5° in the θ direction. These 5 angles between 5° and 35° are shown in black. Also shown in colored straight lines are paths that Čerenkov Light might take. Since the signal will come from the origin, the light will always be reflected to the second focal points of the ellipses (shown by small circles) where PMTs will be located.
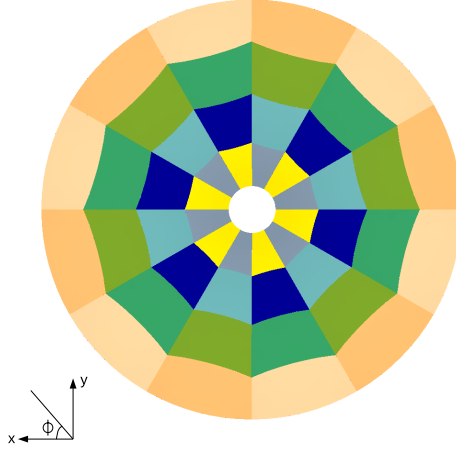

FIG. 3: Front view of all 48 mirrors. All of the 30° slices in the ϕ direction have identical geometry. The origin of the x-y plane is at the center of the mirrors.

IV. DIVIDING PLANES

The interfaces between a mirror and the mirror inside and/or outside of it are defined by planes. These planes are defined by specifying three points in space. These three points for each plane of the "left" mirrors (see figure 4) are shown in table 2. However, when building the mirrors in GEMC, it is convenient to apply the dividing planes to unrotated mirrors (see figure 4) and then rotate the mirrors after the division has been applied. Therefore, the dividing planes must be rotated counterclockwise about the z-axis, the points for these new planes are also specified in table 2.

	Dividing planes for left mirrors			After -15° rotation			angle w/ x-z plane
	x (mm)	y (mm)	z (mm)	x (mm)	y (mm)	z (mm)	β (deg)
M1/M2	0.000	342.103	2259.308	-88.5428	330.4460	2259.3080	44.4392
	0.000	932.040	1678.206	-241.2300	900.2820	1678.2060	
	466.020	807.171	1678.206	241.2300	900.2820	1678.2060	
M2/M3	0.000	170.955	1954.026	-44.2464	165.1298	1954.0260	57.3356
	0.000	640.716	1663.568	-165.8295	618.8841	1663.5680	
	320.358	554.876	1663.568	165.8296	618.8838	1663.5680	
M3/M4	0.000	146.195	1671.014	-37.8381	141.2140	1671.0140	70.1703
	0.000	370.630	1592.839	-95.9261	358.0010	1592.8390	
	185.315	320.975	1592.839	95.9261	358.0010	1592.8390	

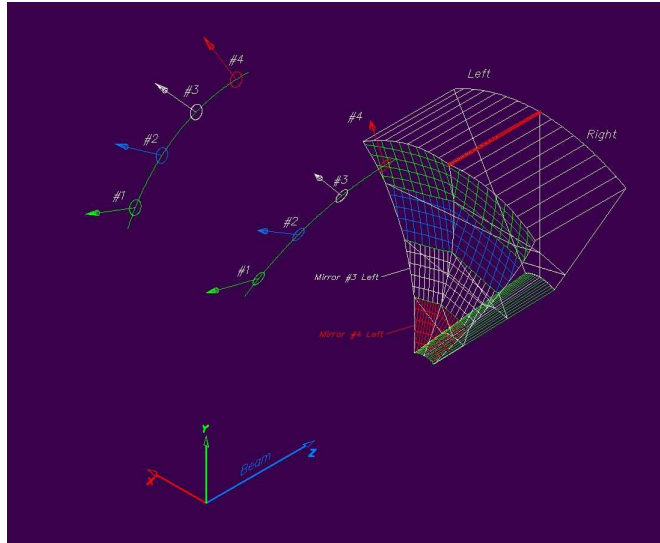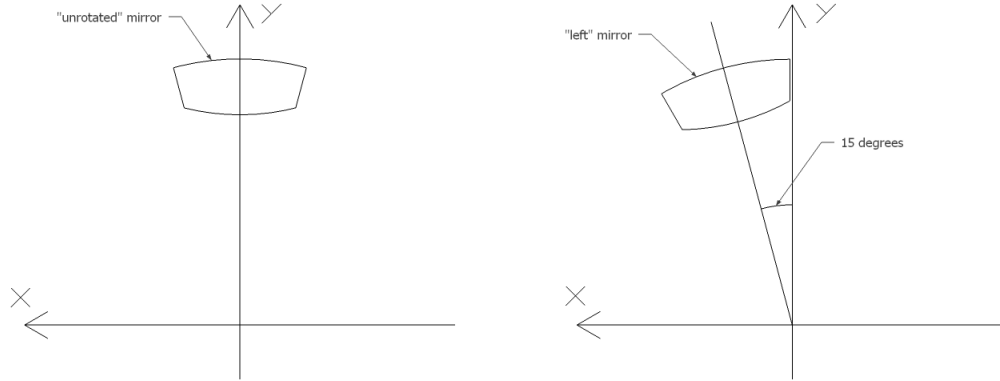Table 2: Values defining the planes that divide the mirrors.

FIG. 4: Rotated and unrotated mirrors. In the lower picture, the directions of the PMTs, specified in table 3, are also shown.

It can be seen in table 2 that the new dividing planes are perpendicular to the y-z plane and therefore form an angle β with the x-z plane (see figure 5). These angles are shown in table 2.
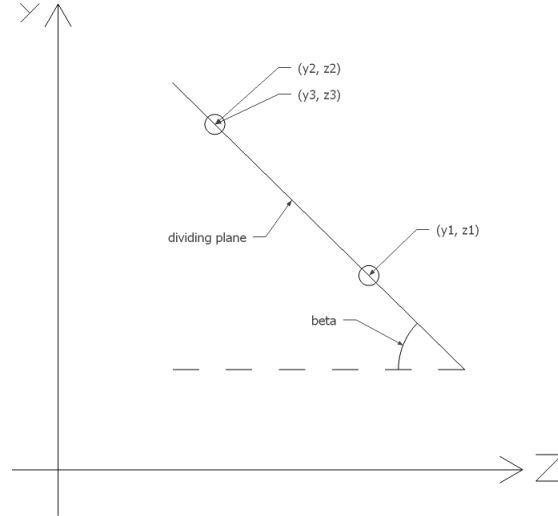
FIG. 5: The dividing planes after the -15° rotation. The β angles are given in table 2.

V. PMTS

The HTCC has 48 PMTs, one for each mirror. The PMTs are located at one of the focal points (the one not at the origin) of its corresponding elliptical mirror. These points are given in the bottom part of table 1 and specify the center of the PMT's face. Note that these points are for the four unrotated mirrors.

In addition to their positions, the PMT directions must also be specified. The direction angles are given in table 3. For GEMC, it is useful to also specify direction vectors, these are also given in table 3. These vectors were found using the common equations for the "direction cosines" of a vector and their lengths were arbitrarily chosen. Note that these directions are for the four rotated "left" mirrors.

	Direction angles			Direction vectors		
	ψ_x (deg)	ψ_y (deg)	ψ_z (deg)	x (mm)	y (mm)	z (mm)
Mirror 1	85.2787	72.1106	161.4570	1.0000	3.7319	-11.5182
Mirror 2	81.6072	56.9940	145.6710	1.0000	3.7318	-5.6575
Mirror 3	78.6436	42.7025	130.4645	1.0000	3.7321	-3.2958
Mirror 4	77.5596	29.7704	116.0198	1.0000	3.7320	-1.8861

Table 3: Direction angles and direction vectors defining the orientation of the axes of the PMTs.

VI. GEMC - THE FIRST SHAPE - A SOLID ELLIPSOID

The final mirror is a piece of this ellipsoid after is has had the appropriate cuts applied to it. It's geometry is described in table 1, however, since this ellipsoid defines the back surface of the mirror, 0.3 mm is added to Rx, Ry, and Rz.

VII. GEMC - THE FIRST SUBTRACTION - A SMALLER ELLIPSOID

The first subtraction is performed in order to turn the solid ellipsoid into an ellipsoidal shell. To do this, another, smaller ellipsoid is created and subtracted from the first. The geometry of this ellipsoid is the same as that of the previous one except for 0.3 mm addition. The absolute coordinates of this smaller ellipsoid are exactly the same as the absolute coordinates of the first ellipsoid, however, since it will be used for subtraction, its coordinates will be relative to the coordinates of the first ellipsoid. Therefore, the relative coordinates of the smaller ellipsoid are (x,y,z) = (0,0,0), and it is unrotated. This smaller ellipsoid defines the front surface of the mirror. See figure 6.
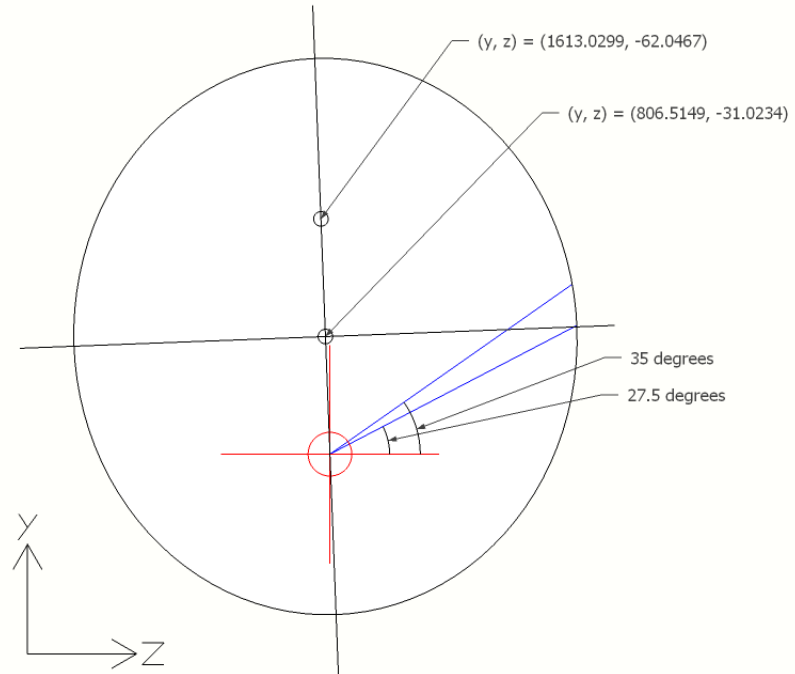

FIG. 6: The ellipse defining the front surface of the mirror. The red lines show the origin of the absolute coordinate system. The ellipsoid is an ellipsoid of rotation and is created by rotating the ellipse about it major axis (y'). Shown in blue are the angles at which Čerenkov light will hit this mirror (mirror 1), 27.5° - 35°. The y'-axis forms an angle of 2.2029° with the y-axis. The x'-axis crosses the x-axis at x = -20997.9801 mm.

VIII. GEMC - THE SECOND SUBTRACTION - A LARGE CUBE

This large cube will be used to cut the ellipsoidal shell approximately in half. The length of a side of the cube is 10,000 mm. The absolute coordinates of the cube's center are (x,y,z) = (0,0,-5000) and it is unrotated. Since it is used for subtraction, its relative coordinates need to

be specified, they are $(x', y', z') = (0, -(\sqrt{(y^2) + (z^2)} - 5000 * sin(\gamma)), -5000 * cos(\gamma))$ and it is rotated about the x-axis by an angle of -γ, where y, z, and γ are given in the top part of table 1.
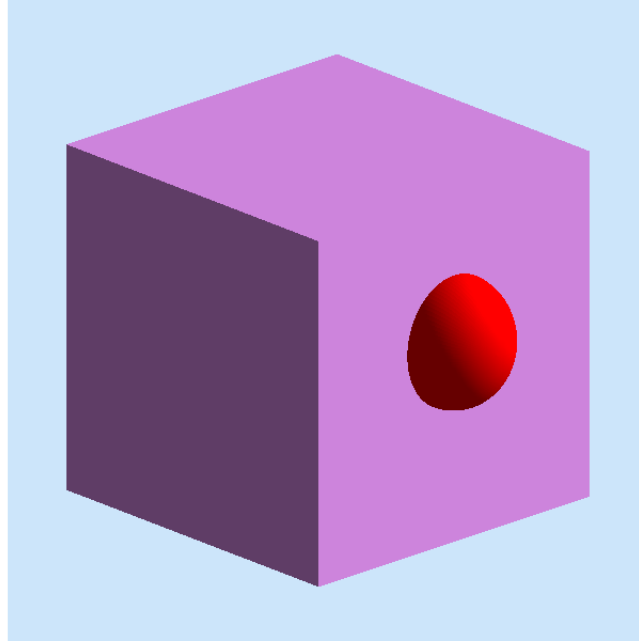

FIG. 7: The ellipsoidal shell and cube used for subtraction, both shown in their absolute positions.
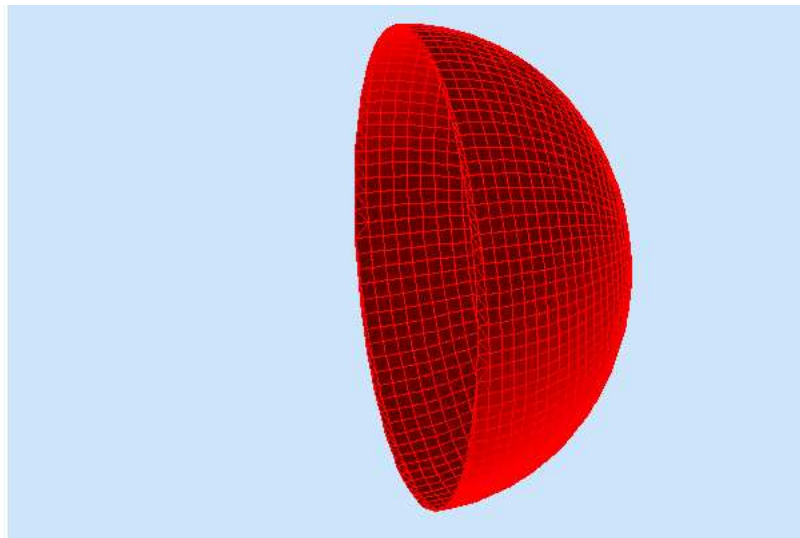

FIG. 8: The result of the subtraction - approximately half of an ellipsoidal shell (shown at a different angle).

IX.   GEMC - THE THIRD SUBTRACTION - A CYLINDRICAL WEDGE

To cut the mirror such that it occupies 30° in the phi direction, a cylindrical wedge is used for subtraction (more like a cylinder with a wedge cut out of it). The cylinder's axis of symmetry

corresponds to the z-axis. Phi starts at 105° and ends at 75° (phi $= 0$ at the x-axis). The relative coordinates of the cylinder's center are $(x', y', z') = (0, -\sqrt{(y^2) + (z^2)}, 0)$ and the cylinder is rotated about the x-axis by an angle of -γ, where y, z, and γ are given in the top part of table 1. See figure 9.
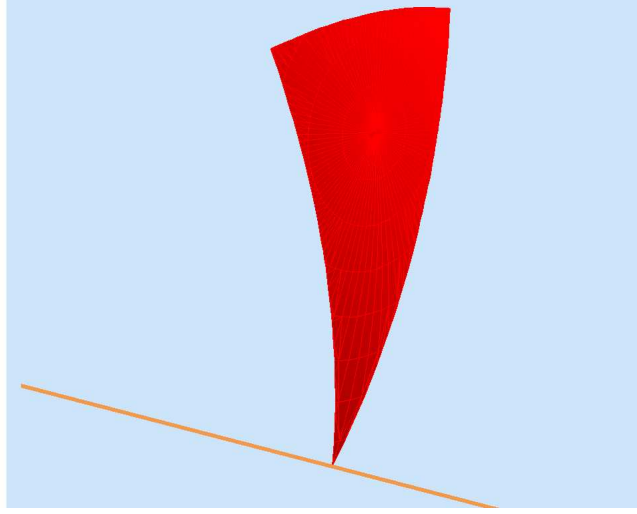

FIG. 9: The result of the subtraction. Beam also shown in orange.

X.   GEMC - THE DIVIDING PLANES

The dividing planes are given in table 2 and figure 5. To apply these cuts, large boxes were created where the top or bottom of the box lies on the dividing plane. If the bottom of a mirror is being cut, the top of the box is used as the dividing plane, if the top of a mirror is being cut, the bottom of the box is used as the dividing plane. See figures 10 and 11.

first, the box is rotated by beta

second, the center of the box is positioned at one of the dividing plane points

third, the box is shifted along this arrow by a distance equal to (+/-) the box's half length

box used to create diving plane
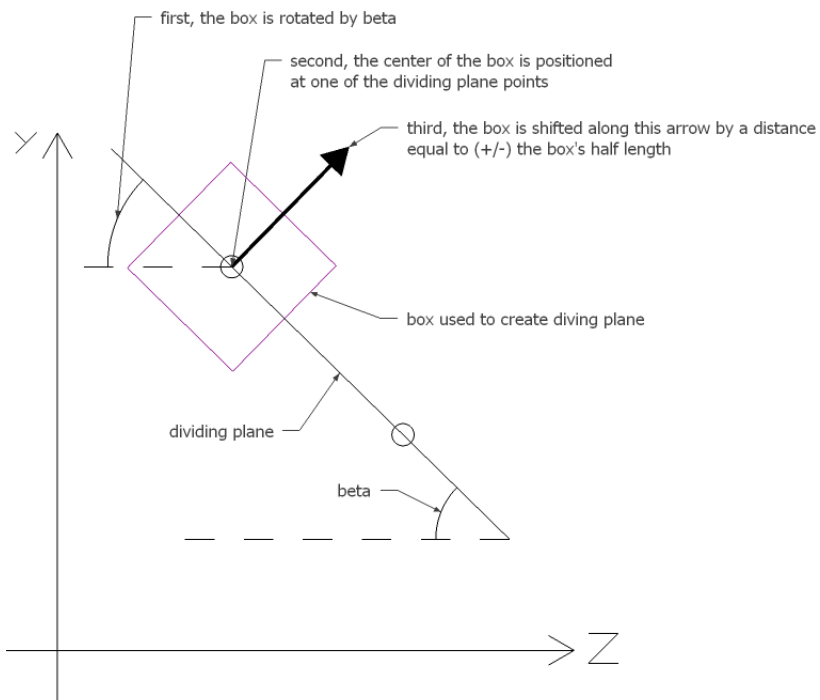
dividing plane

beta

Y

Z

FIG. 10: An illustration of how the boxes are oriented so that one of their surfaces lies on the dividing plane. See figure 5 as a reference.
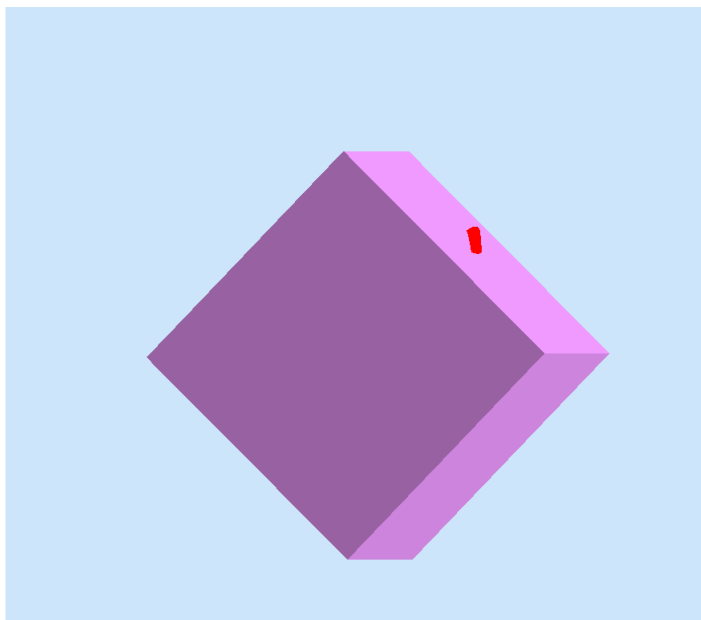

FIG. 11: The subtraction described above. Both objects shown in their absolute positions.
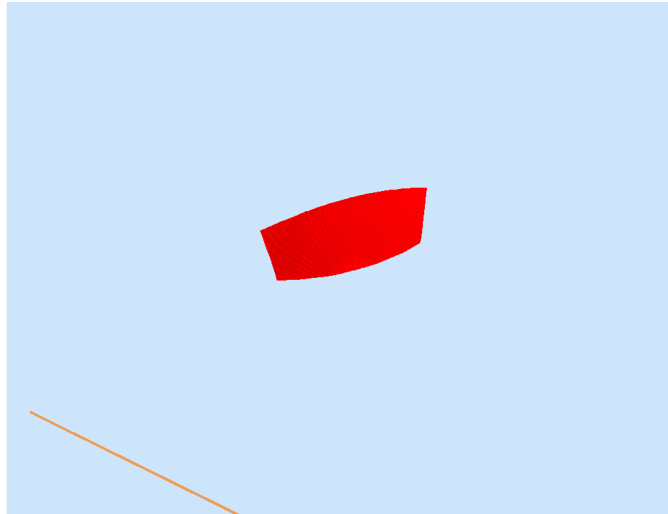
FIG. 12: The result of the subtraction. The beam is also shown in orange.

Six boxes in total are used (bottom of mirror 1, top of mirror 2, bottom of mirror 2, top of mirror 3, bottom of mirror 3, and top of mirror 4), the relative coordinates of each box need to be calculated individually since the equations used depend on what quadrant (both in the absolute and relative coordinate systems) the box is in and whether γ is positive or negative. Figure 13 gives an example where γ is negative and the center of the box is in quadrant I of the absolute coordinate system and quadrant I of the relative coordinate system.
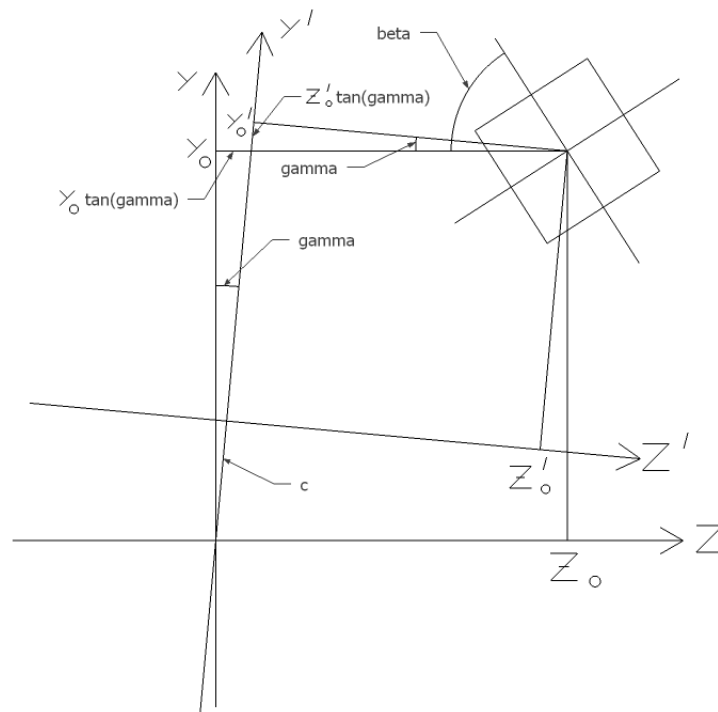

FIG. 13: A drawing illustrating how to convert the absolute coordinates to relative coordinates. In this example, the box is in quadrant I of both coordinate systems.

Figure 13 gives the following results for the relative coordinates:

$$z_0' = cos(\gamma)(z_0 - y_0 tan(\gamma))$$

$$y_0' = z_0' tan(\gamma) + \frac{y_0}{cos(\gamma)} - c$$

where y_0 and z_0 are the absolute coordinates, γ is given in table 1, and

$$c = \sqrt{y^2 + z^2}$$

where y and z are given in the top part of table 1.

The rotation of the box in the absolute system is now counterclockwise by an angle of $\beta - \gamma$.

XI. GEMC - THE TOP OF MIRROR 1 AND THE BOTTOM OF MIRROR 4

When looking down the z-axis, the HTCC mirrors form a circle. Therefore, the top of mirror 1 is cut with a cylindrical shell whose axis of symmetry lies on the z-axis and the bottom of mirror 4 is cut with a cone whose axis of symmetry also lies on the z-axis. See figures 14 and 15.
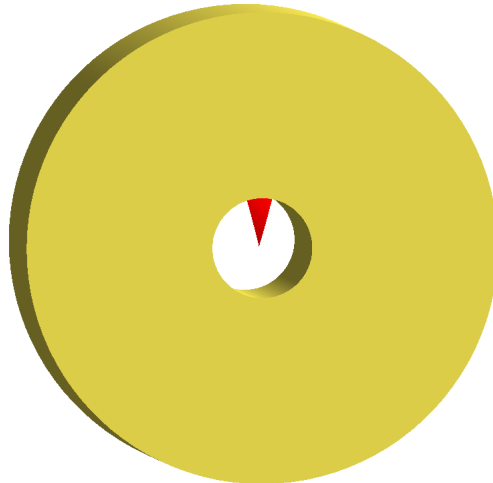

FIG. 14: The cylindrical shell used to cut the top of mirror 1. Its inner radius is 1165.5073 mm, it's outter radius is chosen such that it is large enough to cut away the unwanted part of the mirror, 5500 mm was chosen.
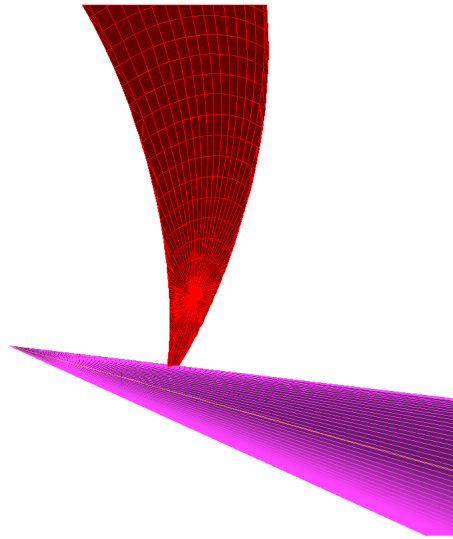
FIG. 15: The cone used to cut the bottom of mirror 4. Its axis of symmetry lies on the z-axis and its surface forms an angle of 5° with said axis. The tip of the cone is at the origin of the absolute coordinate system.

XII.   GEMC - THE PMTS

To model the PMTs, 48 cylinders were used. Their positions and orientations are given in tables 1 and 3, respectively. Figures 16 and 17 show a front view and side view, respectively, of the HTCC mirrors and PMTs.
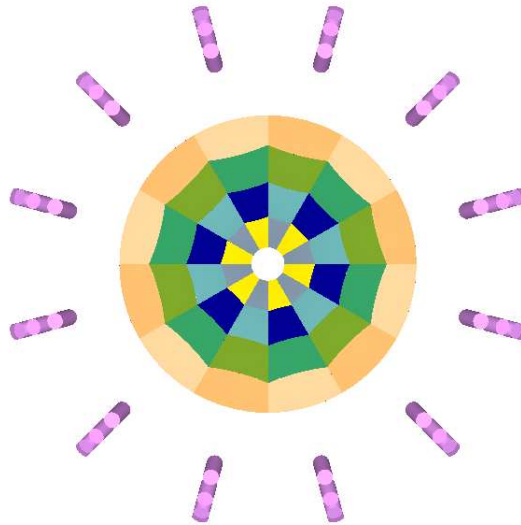

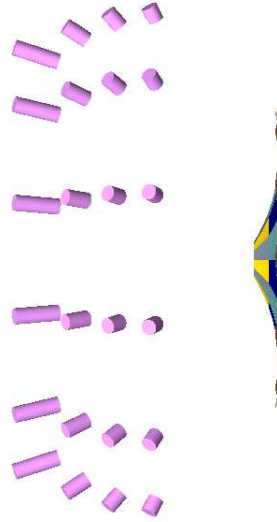FIG. 16: A front view of the HTCC mirrors and PMTs.

FIG. 17: A side view of the HTCC mirrors and PMTs.

XIII.   SUMMARY, CONCLUSION, AND OUTLOOK

To verify that the geometry is correct, the reflectivity of the mirrors was set to 1, and a beam of photons with a spread in the θ and ϕ directions was sent from the target towards the mirrors. Figure 18 shows that these photons were reflected off of the mirrors and were focused at the center of the face of the corresponding PMT, as expected, confirming the correctness of the geometry.

FIG. 18: Photons leaving the target follow the expected trajectory; they are reflected off of a mirror and hit the center of the face of the corresponding PMT.

With the correctness of the geometry verified, the HTCC was added to the database of other CLAS12 components. Figure 19 shows the HTCC in its correct place amidst many of the other CLAS12 components that have already been built in GEMC.
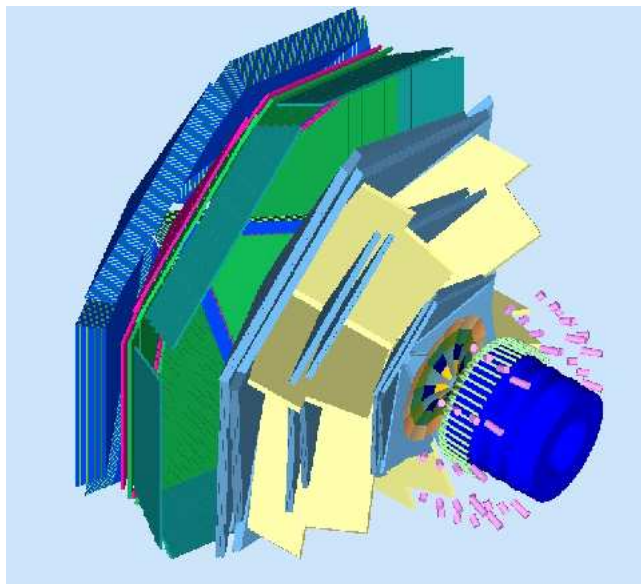

FIG. 19: Several components of the CLAS12 detector, including the HTCC towards the bottom right of the picture.

Construction of the actual HTCC is already underway. Construction and installation are scheduled to be completed by January 2014 and the entirety of CLAS12 is scheduled to be ready to begin experiments in 2015. The simulation data provided by the detectors built in GEMC will be important for comparison purposes when real data becomes available.