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GEANT Simulation of the Čerenkov Counters for the CLAS Spectrometer

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1. Introduction.

1.1. Overview.

The Čerenkov counters (CC) will be used in CLAS to identify electrons and separate them from other charged particles, mostly pions. A program package was built to simulate the CC response using a GEANT description of the whole detector, and to estimate both the efficiency of electron detection and the detection efficiency for other particles. This package is a part of the SHELL description of CLAS. The SHELL framework allows all packages to work together or one can "turn off" some detectors (to estimate their contribution, for example). For the purpose of understanding details of the reflection and absorption of Čerenkov photons, some additional drawing options were included.

1.2. CC package structure.

According to the convention for user-defined packages in SHELL, the CC-package has a structure defined mainly by the `GEANT` convention. The names of all subroutines of the package begin with **"CC"** : `CCINIT, CCSTEP` etc. The SHELL interface calls the subroutines in an order similar to the call of `GUxxxx` procedures in `GEANT`:

```
CCINIC                          ! Reading and interpretation of DATA cards


CCINIT                          ! BEGIN of RUN
||
|| === CCDEIN                   ! GEOMETRY initialization
||
|| === CCHIST                   ! HISTOGRAM and NTUPLE
||                              ! initialization
||
||
|| === (loop over events)
||      ||
||      CCTREV                  ! EVENT beginning
||      ||
||      || ===  (loop over tracks)
||      ||      ||
||      ||      ||
||      ||      CCTRAK          ! BEGINNING of TRACK
||      ||      ||
||      ||      || ===  (loop over steps inside TRACK)
||      ||      ||      ||
||      ||      ||      CCSTEP
||      ||      ||      ||
||      ||      || ===  (end of STEP loop)
||      ||      ||
||      || ===  (end of TRACK loop)
||      ||
||      ||
||      CCDIGI                  ! Calculation of DIGI and
||      ||                      ! storing to ZEBRA banks
||      ||
||      ||
||      CCOUT                   ! END of EVENT
||      ||
|| === (end of event loop )
||
||
CCLAST                          ! END of RUN
```

Subroutine **CCINIT** is called only once in a run before the first event. Here one can define constants for geometry descriptions (`CCDEIN`), book histograms, NTUPLEs, define shapes, sizes and positions of all CC sections, and all boundaries around them. Also the data structures JROTM, JSETS and JDETS are created in this subroutine.

Subroutine **CCTREV** is called before each event. Here one can redefine any parameter for each event.

Subroutine **CCTRAK** permits to make any specific operation at the beginning of each track (including secondary tracks).

Subroutine **CCSTEP**, as GUSTEP in GEANT, is called during track tracing through the active volume. At each CCSTEP call, one can access the information on the coordinates of step, particle and medium characteristics etc. In this subroutine, information on the number of radiated photons and on their directions is stored in the HITS structure.

Subroutine **CCDIGI**, as GUDIGI in GEANT, is called after all tracks are traced. Here one can calculate the CC response for the total event, including information on both primary and secondary tracks. This response is stored in the DIGI structure.

Subroutine **CCOUT** is used for the calculations at the end of each event, e.g. to initialize some parameters and to transfer the information from the DIGI structure to the CODA bank.

Subroutine **CCLAST** is used for end of run actions, e.g. to close files and to save histograms and n-tuples to disk.

1.3. Reference systems and some terminology.

The three main reference systems used in describing the placement of the detector elements are:

MAster Reference System : origin is in the target center, beam direction along Z axis, vertical line along Y axis.

SECtor Reference System is connected with one sector of CLAS with a center in the target center. An (X,Y) plane divides Sector in two symmetric parts. This plane is named *Sector middle plane* or *middle plane*. The X axis is parallel to the Z axis of the MAster Reference System.

SEGment Reference System is connected with each CC segment. The origin is in the target center, the Y axis lies in the *SECtor middle plane* and crosses the target and the center of CC section. The axis X is perpendicular to the middle plane. An (X,Y) plane crosses the centers of the mirrors and the Winston Cones, and is called the *SEGment median plane* or *Median plane*.

2. Package description.

2.1. Geometry.

There are 18 CC segments in each of the 6 Sectors of CLAS. Any segment consists of four mirrors (two elliptical and two hyperbolic), two Winston cones , two photomultiplier tubes, and support frame. The Čerenkov counter gas is assumed to be Freon-12 with the refraction index 1.00108.

The geometry of the Čerenkov detector is defined in the subroutine CCINIT. The subroutine CCDEIN reads data from the file `CCGEOM.DAT` (which is in the directory `SHELL_ ROOT:[DAT]`) and fill parameters in `COMMON /CCP/` . The shapes of elliptical and hyperbolic mirrors are rather complicated; it was impossible to define these shapes in GEANT standard.* All sections are defined as trapezoids (*TRD2*) with 5 parameters. When tracing photons, one should use the real mirror shape. These shapes were defined as second-order curves in the median plane:

$$p_1 * x^2 + p_2 * y^2 + p_3 * x * y + p_4 * x + p_5 * y + 1 = 0$$

A small section of the elliptical mirrors close to the *Middle plane* is flat in order to increase the Čerenkov counter efficiency for electrons with an energy of less than 0.8 - 1.0 GeV.

The Winston cones (WC) are elliptical rotation surfaces. The most suitable coordinate system uses axes u, v which are along and perpendicular to the Winston cone axes. In this system, the WC surface is described by two parameters w_1 and w_2 only,

$$w_1 * u^2 + w_2 * v^2 + 1 = 0$$

For the coordinate transformation from the CC segment system to the WC coordinate system the rotation angle and shifts along X and Y axes were defined. The support frames are described in terms of planes, defined as:

$$p_1 * x + p_2 * y + p_3 * z + 1 = 0$$

For example, for a *Middle plane* $p_1 = -1/BIG; p_2 = p_3 = 0$, where BIG is a big number (10^6).

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* GEANT 3.21 version, installed in CERN at the middle of March,1994 supports such surfaces as ellipses and hyperbolas

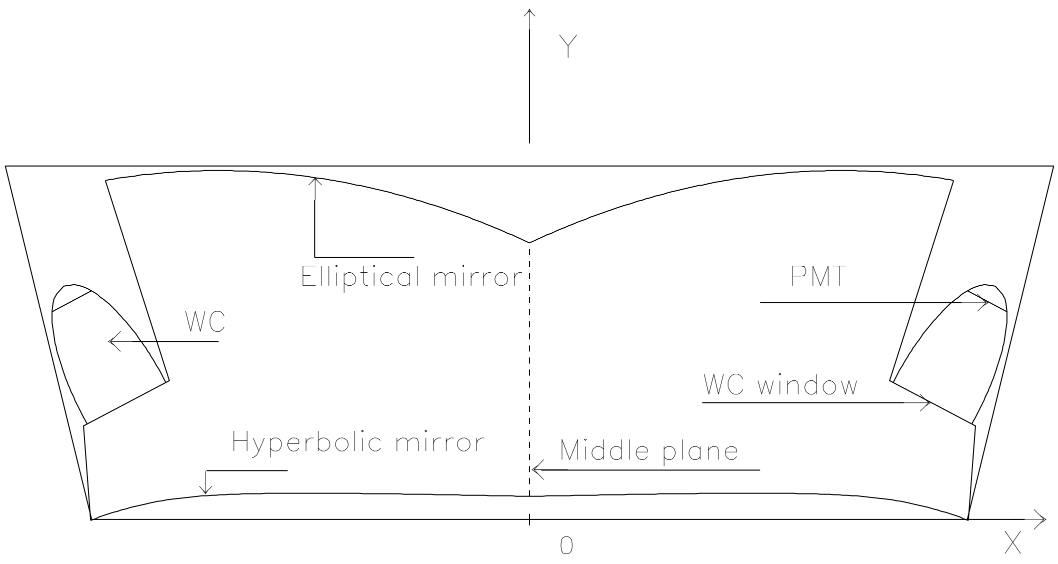

Fig. 1 Median plane view of CC section.

All geometry parameters now are stored in `COMMON /CCP/`

Subroutine CCINIT is used also to "move" CC sections to their positions in the detector. In order to estimate the background produced by interactions with the mirror material, segments of the same thickness as mirrors were positioned inside the CC section. The shapes of these segments are similar to the mirror shapes. We use segments with radii 210.0 and 280.0 cm, respectively. The thickness of hyperbolic mirrors is 0.3 g/cm^2 , elliptical – 0.35 g/cm^2. The mirror material is assumed to be plastic (CH).

2.2. Step procedure (subroutine CCSTEP).

The subroutine CCSTEP is similar to GUSTEP of GEANT and follows the GEANT ideology: when a particle is entering the active volume (named here `CCVO`) then its trajectory is divided into a number of steps; the step length depends on the magnetic field, multiple scattering angle, energy deposition, etc. A subroutine CCSTEP is called after each step, and one can use geometry, particle and media information to calculate and to store information on the response of the CC counters in the HITS bank.

First, the CCSTEP subroutine checks the charge of the particle (uncharged particles can't give a hit!). Then it checks that the particle is in the Freon gas. After that it calculates the particle velocity and checks, that it is large enough to radiate Čerenkov light.

After these checks are passed, the subroutine calculates the coordinates of the beginning and of the end of the step in the *SEGment Reference System*, the time-of-flight from the target to the beginning of the step, and the step length. These data are stored in `COMMON /CCVHIT/` for each track and each step, including secondary tracks.

2.3. Digitization procedure (subroutine CCDIGI)

Subroutine CCDIGI calculates the summary response from all tracks, using HITS information. For any stored part of the track the number of photoelectrons is determined. The mean number of photoelectrons which have been detected is

$$N_{p.e.} = L\frac{\alpha}{\hbar c}\int \varepsilon_{ref}(E)\varepsilon_{pmt}(E)\sin^2\theta_c(E)dE,$$

where E is the photon energy, ε_{pmt} is the quantum efficiency of the photomultiplier, ε_{ref} is the light reflection efficiency, and $\sin^2\theta_c(E) = 1 - \frac{1}{\beta^2 n^2(E)}$.

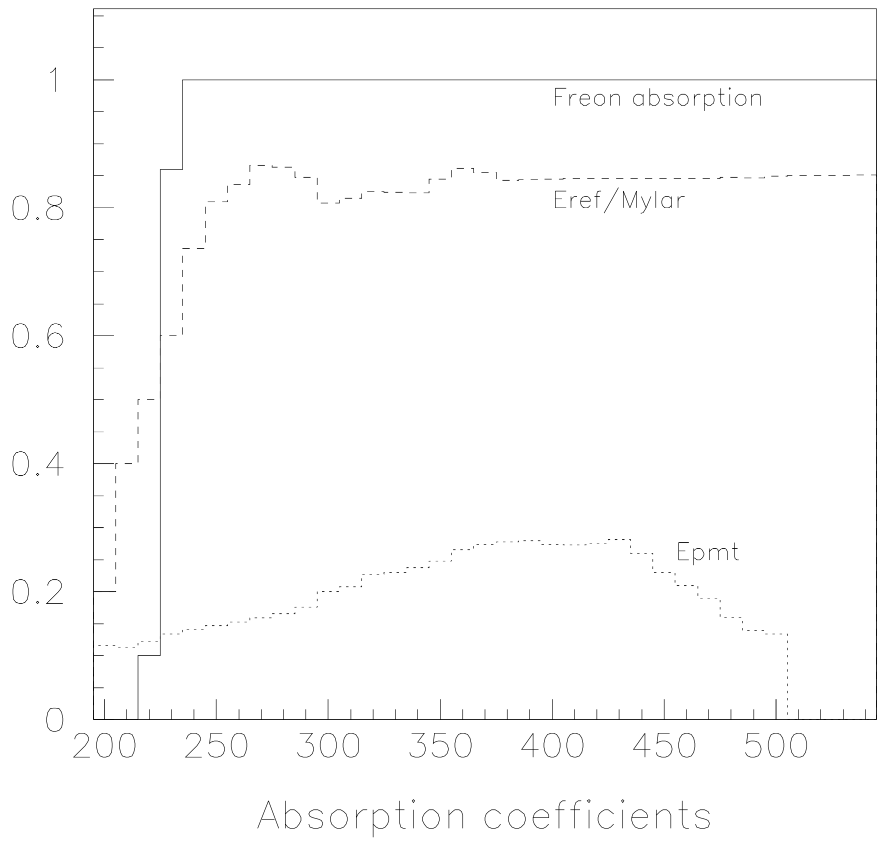

Fig. 2 Wavelength dependence of the absorption coefficients
— *Freon absorption* - - - *Reflection efficiency* ..... *PMT quantum efficiency*

Fig. 2 shows the ε_{pmt} and ε_{ref} coefficients as a function of λ. The calculation of the integral

$$I_0 = \int \varepsilon_{ref}(E)\varepsilon_{pmt}(E)dE$$

gives the value $I_0 = 0.246\ eV$. For Freon 12 (CCl_2F_2), n=1.00108 and $\sin^2\theta_c =$ 0.0021565. The estimated number of photoelectrons is:

$$N_{p.e.}/L = 370 I_0 \sin^2\theta_c = 0.196\ cm^{-1}.$$

The calculations have been made assuming two reflections from the mirrors. The random number of radiated photons in one step is determined using Poisson distribution:

$$N_{phot} = l_{step} * N_{p.e.}/L$$

If a photon reaches the PMT, it is assumed to produce one photoelectron. Photons are radiated from random points along the track. The number of radiated photons and the polar angle between particle and photon directions are calculated taking into account the particle velocity. For each photon, a random azimuthal angle was generated.

Ray tracing for each photon is based on the calculation of the distance to the nearest surface. The photon is either reflected from this surface (mirrors, inner surface of WC) or absorbed (in any other case). Reflection points become new start points for the photon ray tracing, and so on.

When the photon crosses the boundary plane between segments, a new start point in a new CC *SECtion Reference System* is defined. Boundary planes at the edges of the Čerenkov counters in the Sector (CC Segments number 1 and 18) are considered to be mirrors, and the photon can be reflected by them.

The response information is obtained in the following form:

i. The number of hit PhotoMultiplier Tubes (PMT).

ii. The number of photoelectrons for each PMT. It is proportional to the ADC signal.

iii. The minimum time-of-flight for all photons that have reached the PMT. It is proportional to the TDC value (one channel corresponds to 50 ps).

2.4. Subroutine CCOUT.

Subroutine CCOUT stores all calculated DIGI values to the CODA bank for future usage in `RECONSTRUCTION` and `ANALYSIS` procedures. Histograms and N-tuples can be filled in any subroutine.

3. KUIP commands for CC package

When processing events, one would like to see a picture of the ray tracing in the event. For example, one may wish to know why the efficiency of electron detection at some angle differs from the mean efficiency. For this purpose KUIP – command `CC/EVENT` was implemented.

You can obtain a list of `KUIP` commands by typing " `HELP` " after executing `CLASSIM`. The format of the `CC/EVENT` command is :

`CC/EVENT [Factor] [U] [V]`

`[Factor]` - Scale factor for the picture

`[U]` - Horizontal shift

`[V]` - Vertical shift

Using the scale factor and U, V shifts one can not only see the complete event, but also some details. Usually, it is sufficient to use command
" `CC/EVENT !` " `< Return >`
which means that default parameters are used to obtain a proper picture. The program draws a picture in *Segment median plane*, including:

i. Projections of the frames for those CC sections which have been crossed by photons (BLACK);

ii. The trajectory of particle (GREEN) ;

iii. Photon ray tracing, in RED in case the photon has reached the PMT and in BLUE otherwise.

One can also save the picture as a PostScript file and print it later.

We used these capabilities to understand the relatively low electron efficiency for electrons that traverse the CC segments number 11 and 12. Fig. 3a shows an example of these events.

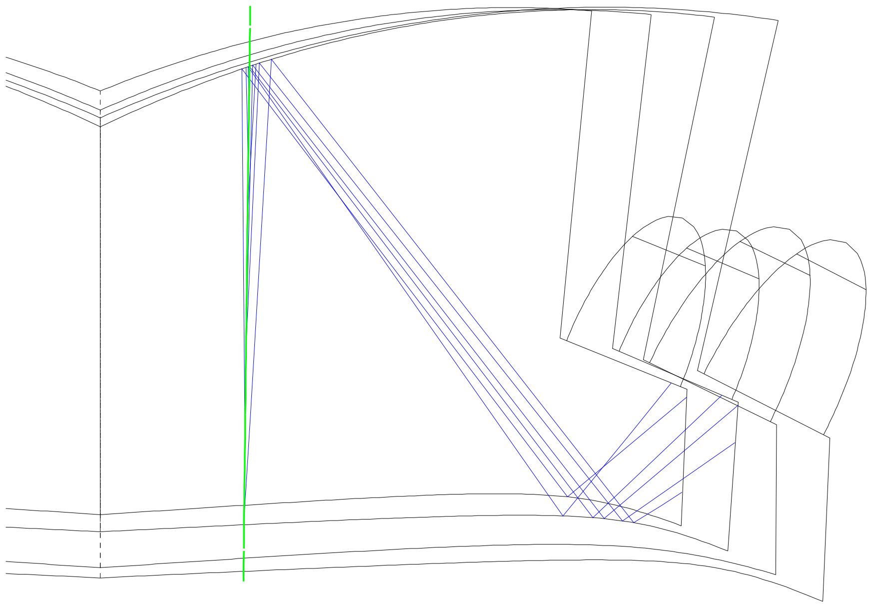

Fig. 3 a) Old geometry

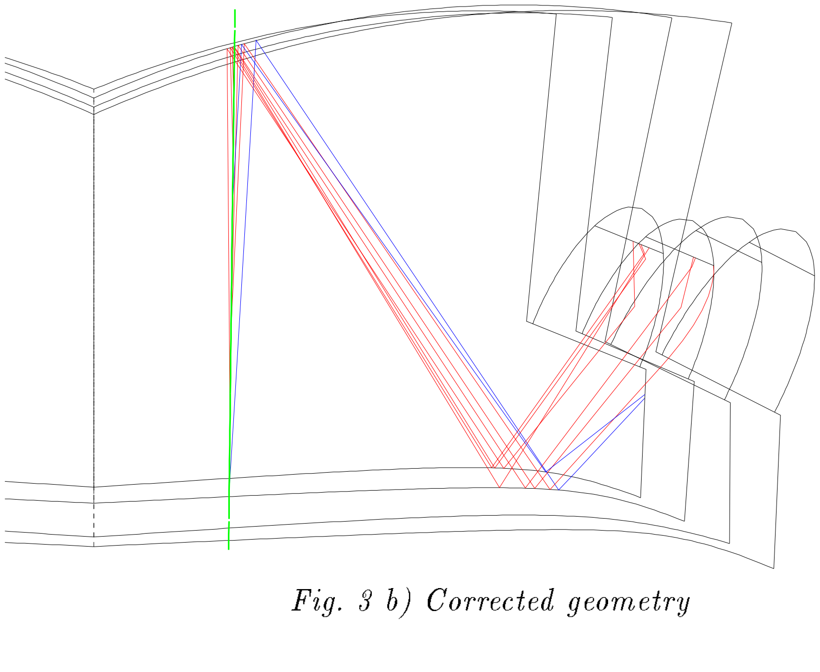

Fig. 3 b) Corrected geometry

One can see in Fig. 3a that most of the reflected photons miss the Winston cone entrance window. To increase the efficiency for the electron detection, the elliptical mirror number 11 has to be turned around the Z axis by an angle of 1^o. Fig. 3b shows the same event after this correction. One can see, that now most of the photons have reached the photocathode.

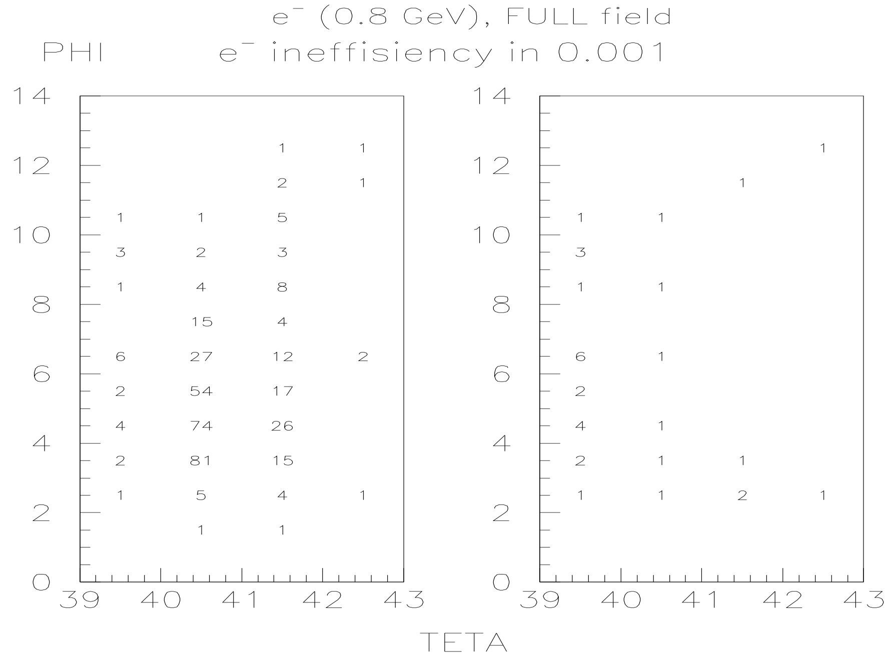

Fig. 4 Electron inefficiency vs angles TETA and PHI
Left - old mirror placement , Right - new placement

Fig. 4 shows the inefficiency for electrons in this small region of $TETA$ and PHI angles. One can see that the inefficiency has been reduced significantly by this correction.

4. Estimation of the Čerenkov counters efficiency.

The efficiency of the Čerenkov counters is defined here as a probability for a particle that is crossing a CC segment to produce a hit in any CC segment. The threshold for a hit is assumed to be one photoelectron. In simple cases, one can use the mean number of photoelectrons for the efficiency estimate. This estimate is based on the assumption that photoelectrons are distributed according to Poisson's law. In CLAS the large aperture of the CC counters and the small angle of the Čerenkov cone result in correlated photon detection. Because of these correlations the distribution may differ from the Poisson distribution.

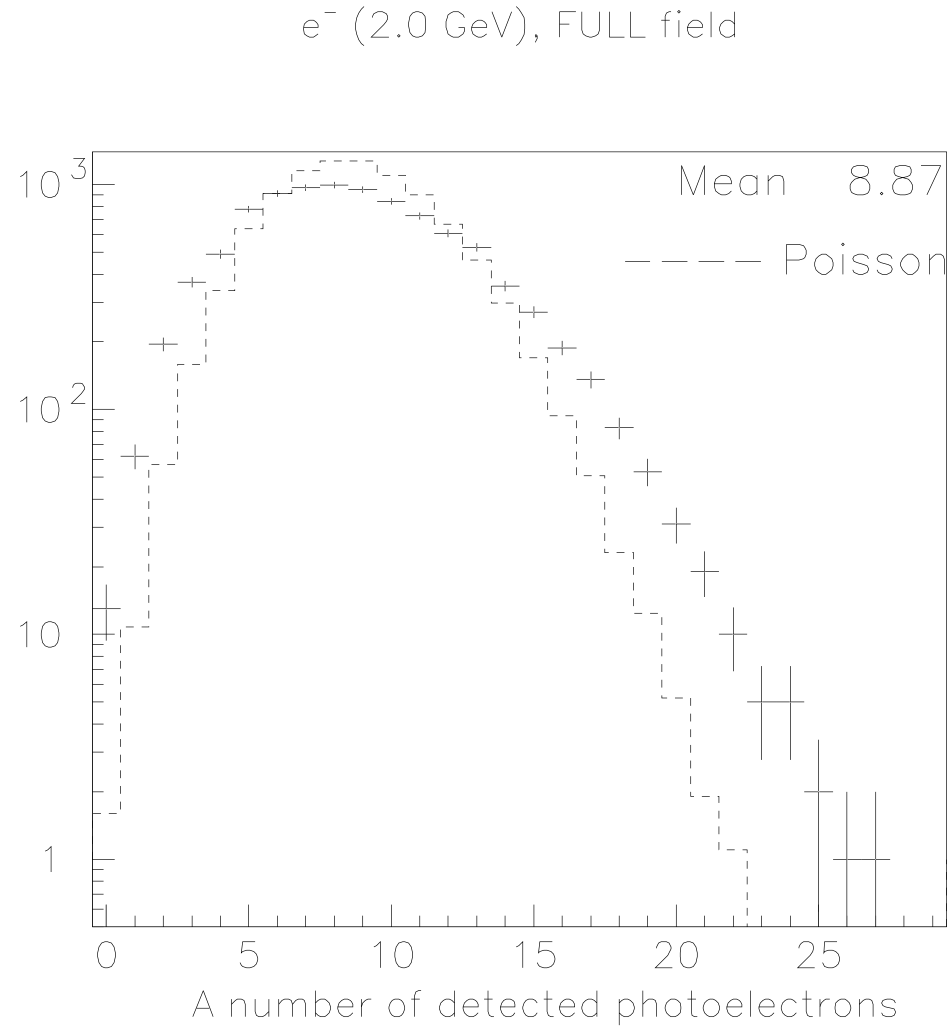

Fig. 5 A number of photoelectrons distribution

In Fig. 5 one can see the distribution of the number of detected photoelectrons for one primary electron from simulated events. The dashed curve stands for a Poisson distribution with the same mean value (8.87). One can see from this figure, that the "experimental" distribution is wider than the Poisson distribution, and the probability to obtain zero photoelectrons is significantly different in both cases. This is a good reason to have a full GEANT simulation program to estimate the efficiency correctly.

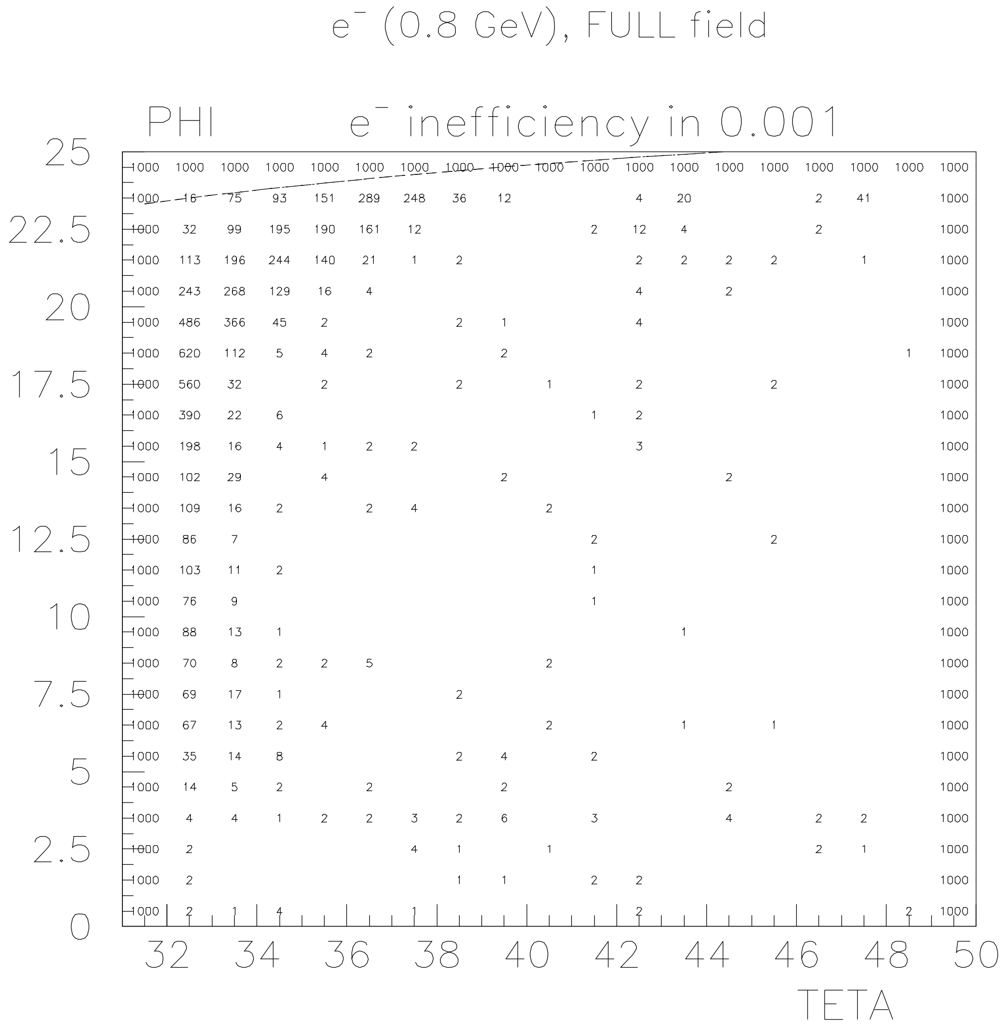

Fig. 6 Electron inefficiency versus angles TETA and PHI

Fig. 6 shows the value of electron inefficiency due to the Čerenkov counter response, only. The electron energy was 0.8 GeV/c, the range of polar angle $TETA$ was $27^o \div 57^o$, the range of azimuthal angle PHI was $0^o \div 25^o$. The polar angle range was determined by the condition that the particles cross the CC segment. The polar angle range is generally different for different momenta and different magnetic field values. The line in the figure corresponds to the shadow cast by the magnet coil. One can see that the value of electron inefficiency is of order 10^{-3} for the most of the angular region covered by Čerenkov counters.

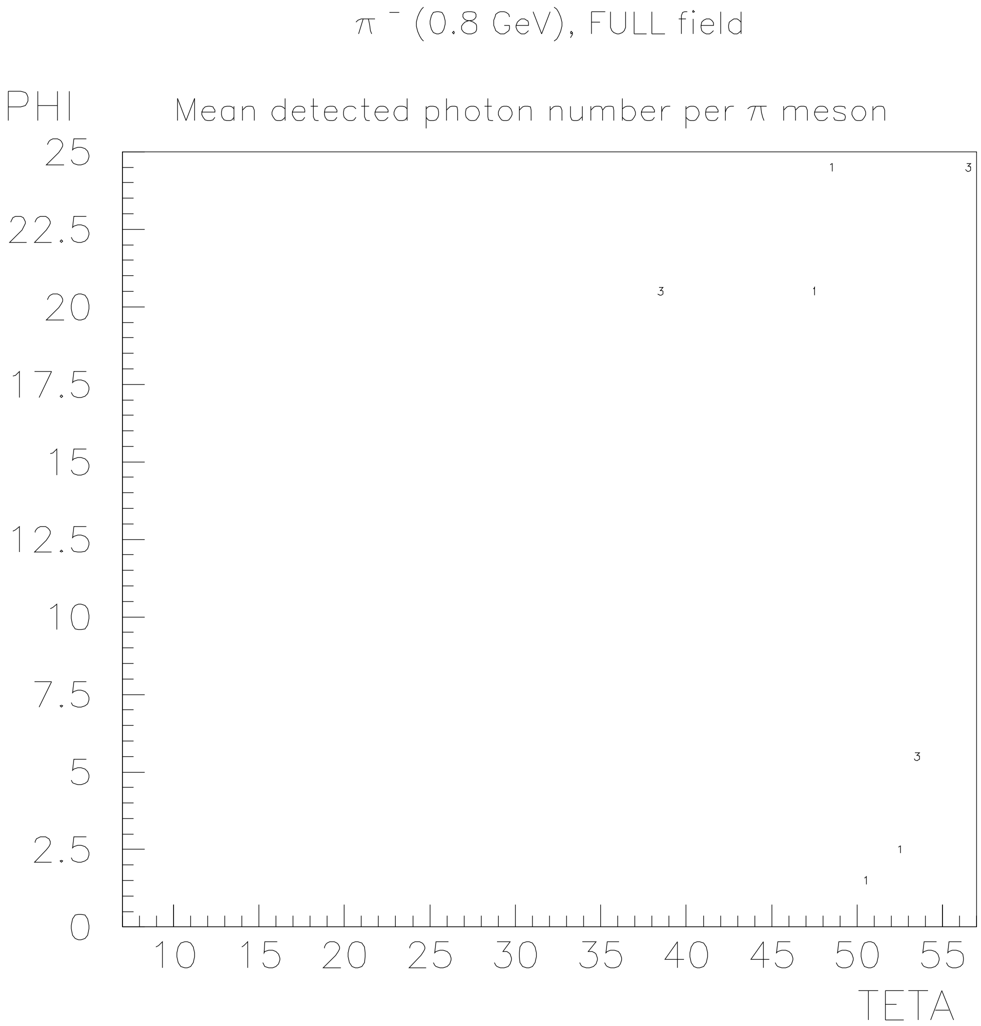

Fig. 7 Efficiency of pion registration.

The main purpose of the Čerenkov counter in CLAS is $\pi - e$ rejection, so the response of CC for π mesons is important. The threshold of Čerenkov light radiation for pions is about 2.8 GeV (Freon-12 gas), but it is possible (in principle) to detect lower momentum pions via fast secondary δ electrons scattered by initial pions.

Fig. 7 shows the number of detected photoelectrons for initial π mesons with momentum 0.8 GeV/c. There were only 7 hits from 24000 initial π mesons. One can see that the number of photoelectrons in case of initial π mesons is also rather small. It should be mentioned that we don't include the Electromagnetic Calorimeter in this simulation. Additional material of the magnetic field shields of PMT and the Winston Cone material should be included into the GEANT geometry to make this estimate more precise.

5. Simulation tasks and future code development.

1. Implement correct geometry and create new tracing code for the internal area of the Winston cone.
2. Add material for WC and magnetic field shielding.
3. Estimate efficiency at small angles θ.
4. Optimize mirror placement.
5. Repeat the simulation for Freon-114 gas (n = 1.005).