Error and Background Radiation Analysis for the Hall C Compton Polarimeter

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Table of Contents

ABSTRACT

Many of the experiments that run in Hall C at Thomas Jefferson National Accelerator Facility require a precise measurement of the electron-beam polarization. Along with the current Moller Polarimeter, a Compton Polarimeter is going to be added, which is non-destructive to the beam, allowing the polarization to be measured at the same time that data is taken. Current simulations for the Compton Polarimeter, which track the properties of the particles as they go through the magnetic chicane and into the detectors, neglect the background radiation that is created, especially when the beam passes through a focusing aperture before it enters the optical cavity of the polarimeter. When the beam goes through this aperture, some of the electrons in the beam halo will collide with the metal, thus creating background radiation. The focus of this project was to adapt the current Monte-Carlo-based Compton simulation to determine the perimeters as to when the background radiation produced by the beam halo will cause significant errors in the data taken in the detectors. Using Fortran, the aperture was created in the Geant3 Monte-Carlo simulation. Then, simulations of the beam halo background radiation were run, and the rates of the particles detected for both backscattering and the beam halo were analyzed. It was found that the halo will not be a significant problem in the detectors, but it will be more of a problem in the photon detector than the electron detector. For the backscattering and halo events to differ by a factor of ten, the fraction of the beam in the halo needs to be smaller than 2E-10, which is 20 times smaller than expected. This means that as long as the beam is focused, the backscattering events will dominate. Setting certain hardware thresholds and software cuts on the detectors, which will cause them to only read a certain energy range, can also improve the ratio of backscattering to halo events. These findings will allow the scientists using the Compton Polarimeter to reduce and estimate the relative size of the contamination coming from the beam halo background radiation. The simulation will also be useful for the design of the 12GeV Compton Polarimeter, allowing scientists to see if the size of the aperture must change as the beam's energy increases and the halo becomes worse

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AMBER MCCREARY, PATRICIA SOLVIGNON, DAVE GASKELL

INTRODUCTION

The experiments that run at Thomas Jefferson National Accelerator Facility with a polarized electron-beam require a precise measurement of the polarization. The current Moller Polarimeter in Hall C requires that a target be placed in front of the beam, therefore destroying the beam when the polarization is measured. Therefore, a Compton Polarimeter will also be added to the beam line, which, unlike the Moller, is non-destructive to the beam, thus allowing data to be taken while the polarization is being measured.

In order to measure the polarization of the beam, the Compton Polarimeter utilizes the concepts of Compton scattering of electrons off of photons. When the polarimeter is turned on, the beam is bent through the first two dipoles and into an optical cavity (See Figure 1). Inside the optical cavity is a laser of known wavelength at an angle of about two degrees relative to the beam. When the electron and photon interact, the photon will be backscattered into a photon detector while the electron, having lost some of its energy in the interaction, will bend differently through the third dipole and into an electron detector (assuming it has lost enough energy). The rest of the beam is bent through the third and fourth dipoles and into its original path [1]. By measuring the asymmetry between two measurements of Compton scattering with parallel and anti-parallel polarization of the laser and electron beam, the polarization of the electron beam can be found using the simple relation: $A_{exp}=P_e P_\gamma A_l$ where A_{exp} is the experimental asymmetry (measured during experiment), P_e is the polarization of the beam, $P\gamma$ is the polarization of the laser, and A_l is the theoretical asymmetry [2].

There are two main methods for measuring the polarization of the beam: the differential and the integrated method. The differential method, which measures the asymmetry event by event, is much faster and precise. The integrated method, however, takes the average asymmetry over a number of events. Although it is not as fast, it does not create a significant amount of dead time in the detectors as the differential method does [1]. In this part of the project, it was advantageous to find the amount of time the polarimeter will need to be run for in order to yield a 1% error in the polarization measurement, depending on the polarization of the beam, for both methods so that the accuracy versus time can be compared to see which method is more efficient.

The second part of the project analyzes background radiation. The current simulation of the Compton Polarimeter, which tracks particles as they move through the magnetic chicane and into the detectors, neglects the background radiation that will be created. In this project, the type of background radiation studied was the beam halo, in which some of the electrons in the beam are located in the Gaussian tails of the spatial coordinates, creating a “shadow” halo (Figure 2). The halo electrons will be bent differently than the main beam. Not only can the halo interact directly with the electron detector, but it can also collide with metal whenever the beam is sent through a focusing aperture about 1 centimeter wide both before and after the optical cavity. Since the halo causes the beam to be wider than expected, the halo will interact with the metal, creating a multiple particle spray and therefore causing undesirable readings in the detectors. The focus of this part of the project was to find the parameters that would cause the entries in the detector from Compton backscattering compared to the halo to differ by at least a factor of ten [3].

METHODS AND MATERIALS

Software Used/In General:

Throughout both the counting method time analysis and the beam halo study, a Geant3 Compton Simulation was used to simulate the polarimeter. The simulation tracked the particles, both electrons and photons, and recorded their characteristics (energy, momentum, trajectory, etc.) as they traveled through the polarimeter and interacted in the optical cavity. The Fortran-based code for this simulation was already written, but was able to be adapted. Once the preferred variables were adjusted, an "hbook" file was compiled for a certain number of random events (within the physical limit achievable during the experiment), which contained all of the information from the simulation. By plotting histograms in paw++ of values from the "hbook" file, the desired results could be found. In addition, Geant++ was used to interactively check the electron and photon trajectories through the chicane elements.

Finding Run Time Necessary for 1% Error from Differential Counting Method:

In the differential counting method, all of the physics quantities of the scattered photon and electron are measured event by event in '*Nb*' bins. The polarization is measured in each bin and the weighted mean gives the electron polarization. This is the most accurate counting method because it records the information of each event, yet it causes a significant amount of dead time in the detector readouts [2]. Therefore, a large number of events can be missed. The necessary t_D to achieve an accuracy of $(\Delta P_e/P_e)$ is [2]:

$$t_D = \frac{1}{\sigma_t \cdot L \cdot \left(\frac{\Delta P_e}{P_e}\right)^2 \cdot P_e^2 \cdot P_\gamma^2 \cdot \left\langle A_l^2 \right\rangle} \tag{1}$$

where 'σ_t ' is the total cross section, 'L' is the luminosity, and 'A_l' is the theoretical asymmetry. $< A_l^2 >$ is given by [2]:

$$\left\langle A_l^2 \right\rangle = \frac{\int_{\rho \min}^{1} d\rho * \varepsilon(\rho) * \frac{d\sigma}{d\rho}(\rho) * A_l(\rho)^2}{\int_{\rho \min}^{1} d\rho * \varepsilon(\rho) * \frac{d\sigma}{d\rho}(\rho)} \tag{2}$$

where $d\sigma/d\rho(\rho)$ is the differential cross section and $\varepsilon(\rho)$ is the detection efficiency, which is assumed to be 100% for this study.

Since the experiment wants less than a 1% error in the polarization measurement, $(\Delta P_e/P_e)$ is set to .01 in equation (1). Also, because the necessary times are only being compared, a value can be assigned for P_e and $P\gamma$. In this project, the electron-beam polarization was set at 70, 75, 80, and 85%, and the laser was 100% polarized. In order to extract the values from equations (1) and (2) from the simulation, histograms of the cross section, luminosity, and asymmetry had to be plotted by creating a Fortran based code called a 'kumac,' then executing it in paw++. By multiplying and integrating histograms when necessary, the time needed could be found.

Finding Run Time Necessary for 1% Error from Integrated Counting Method:

During the integrated counting method, the data are collected in groups and only the average characteristics are accessible. Because this method calls for integration over the group of collected events, only positive values of the asymmetry can be used to avoid integrating over a negative area. This will be done by placing a hardware threshold on the photon detector so that only photons greater than some minimum energy will be recorded. Knowing the detection efficiency and the energy threshold range, the average number of events can be used to calculate the asymmetry and therefore, the beam polarization [2]. Although this counting method is not as accurate as the differential method, it does not require the same amount of processing in the data acquisition system and does not create a significant amount of dead time in the detectors. However, this method directly depends on both the detection efficiency and the energy threshold, whereas the differential method does not depend on either.

The time t_I needed to achieve an accuracy *($\Delta P_e/P_e$)* is [2]:

$$t_I = \frac{1}{\sigma_t \cdot L \cdot \left(\frac{\Delta P_e}{P_e}\right)^2 \cdot P_e^2 \cdot P_\gamma^2 \cdot \langle A_l \rangle^2} \tag{3}$$

where $<A_l>$ is given by [2]:

$$\langle A_l \rangle = \frac{\int_{\rho\,\min}^{1} d\rho * \varepsilon(\rho) * \frac{d\sigma}{d\rho}(\rho) * A_l(\rho)}{\int_{\rho\,\min}^{1} d\rho * \varepsilon(\rho) * \frac{d\sigma}{d\rho}(\rho)} \tag{5}$$

A similar method of plotting the cross section, luminosity, and asymmetry and then multiplying/integrating histograms can be used to extract the time needed from the simulation as was used for the differential method.

Analyzing the Effects of the Beam Halo

There were many adaptations that needed to be made to the Geant3 Compton Simulation to properly simulate the beam halo. First, the focusing aperture had to be incorporated into the simulation. Using files that are intrinsic to Geant3, two disks of solid metal that had the same radius as the main pipe were created first. Then a 1 cm wide, 2 cm high, and 1.2 cm thick rectangular hole was removed from the metal disk to simulate the aperture (Figure 3). The disks were placed at 62.2 cm and -62.2 cm from the center of the optical cavity. In addition to creating the aperture, certain variables in the simulation had to be changed to allow the simulation to become more realistic, such as the emittance, beam size, the beam energy spread, etc. However, in the simulation, it was assumed that the halo does not interact with the laser, which is unrealistic but is not expected to have a big effect.

Once the simulation was changed, it had to be run with/without the aperture and also with/without the halo to see the effects the halo going through the aperture had on the counting rates in the detectors. The Geant3 simulation could be run in a matter of hours, depending on the number of events. For this analysis, there were two types of simulations that could be compiled: the ‘compton’ and the ‘compton++.’ The second simulation is interactive in that it draws the particles as they go through the polarimeter. Figure 4 is a simulation of Compton backscattering events in the polarimeter while Figure 5 shows the beam halo events hitting the aperture inside the cavity.

To find the effects on the energy deposited in the detector from the halo, the first type simulation had to be used. ‘Hbook’ files were created with certain number of events and then the histograms of the energy values were analyzed. Certain cuts were placed on the energies in order to only look at particles that lose enough energy to make it into the electron detector. Also, the simulation considers that every electron interacts with a photon. This is unrealistic in that it is very rare for an interaction to occur. To account for this, the values from the histograms had to be weighted by the cross section and luminosity, and then divided by the number of events generated to give the correct rate values.

RESULTS

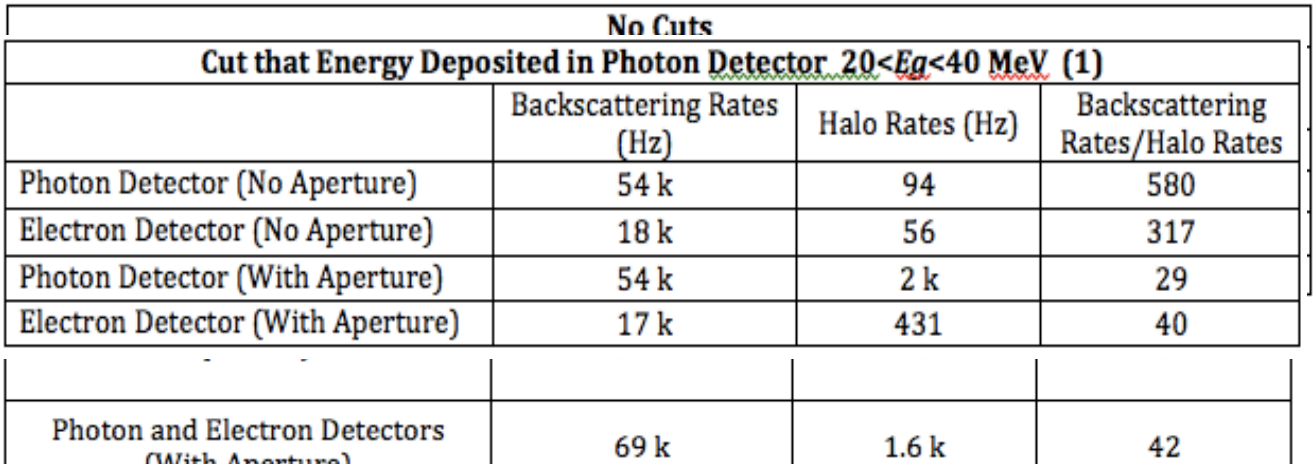
t_D and t_I for 1% Error:

The time needed for 1% error in the polarization was found for the differential and the integrated method using just Compton backscattering. The results are illustrated in the table below, with either no cut on the asymmetry, the asymmetry positive, or the asymmetry negative:

Polarization	Time (minutes)	No Cut	A_l>0	A_l<0
85%	t_D	6	13	233
	t_I	30	16	293
80%	t_D	7	15	263
	t_I	34	19	330
75%	t_D	8	17	299
	t_I	39	21	376
70%	t_D	9	19	344
	t_I	49	24	431

Analyzing the Effects of the Beam Halo:

The Compton Simulation was run with and without the beam halo and also with and without the aperture in the beam line. The desired ratio between backscattering events and halo events was (Rates for backscattering)/(Rates for Halo)> 10. The fraction of the beam in the halo used was 2E-10.



No Cuts

Cut that Energy Deposited in Photon Detector 20<Eg<40 MeV (1)

	Backscattering Rates (Hz)	Halo Rates (Hz)	Backscattering Rates/Halo Rates
Photon Detector (No Aperture)	54 k	94	580
Electron Detector (No Aperture)	18 k	56	317
Photon Detector (With Aperture)	54 k	2 k	29
Electron Detector (With Aperture)	17 k	431	40

Photon and Electron Detectors (With Aperture)	69 k	1.6 k	42

Cuts (1) & (2) = Coincidence			
	Backscattering Rates (Hz)	Halo Rates (Hz)	Backscattering Rates/Halo Rates
Photon and Electron Detectors (No Aperture)	18 k	56	317
(With Aperture)	17 k	431	40

The energy distributions versus rates in the photon and electron detectors can be seen in Figures 6 and 7, respectively.

CONCLUSION

It can be seen that the run time necessary for 1 % error increases as the polarization of the beam decreases. The differential method (with no cut on the asymmetry) is the faster method by a significant amount. Yet, the amount of computing power needed to run with this method and the dead time created in the detector readouts are large enough that it is not worth the faster time. Therefore, the integrated method will be used for the experiment, yet the results show that there needs to be a threshold established that will keep the asymmetry positive. The differential method will, however, be used on occasion to check systematic effects by comparing the results to those from the integrated method.

It was found that the background radiation from the beam halo will not be a significant problem, yet it will be more of a problem in the photon detector than the electron detector. In order for the backscattering and the beam halo events to differ by a factor of ten, the fraction of the beam (with no cuts) in the halo has to be 2E-10, which is 20 times smaller than what was expected. Placing cuts on the energies recorded in both detectors, which is done using hardware thresholds and software cuts, gives the optimal ratio between the backscattering and halo events. Since the ratios with these cuts are greater than ten, the fraction of the beam in the halo can be increased. After careful analysis, the maximum fraction of the beam in the halo to get a factor of ten difference can be as high as 1E-9. Using the hardware cut eliminates events from being recorded, and thus, the scientists using the Compton polarimeter have to decide whether it is more efficient to have all of the events or eliminate as much halo as possible. In general, however, as long as the beam is focused, the backscattering will dominate the halo rates.

ACKNOWLEDGEMENTS

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REFERENCES

[1] P. Solvignon. Private Communication.

[2] G. Bardin et al., "Conceptual Design Report of a Compton Polarimeter for Cebaf Hall A." 9 May 1996.

[3] D. Gaskell. Private Communication.

[4] "Compton Polarimeter." *Hall C Polarimetry*. Hall C at Thomas Jefferson National Accelerator Facility, 7 Apr. 2010. Web. 28 July 2010.

NECESSARY FIGURES

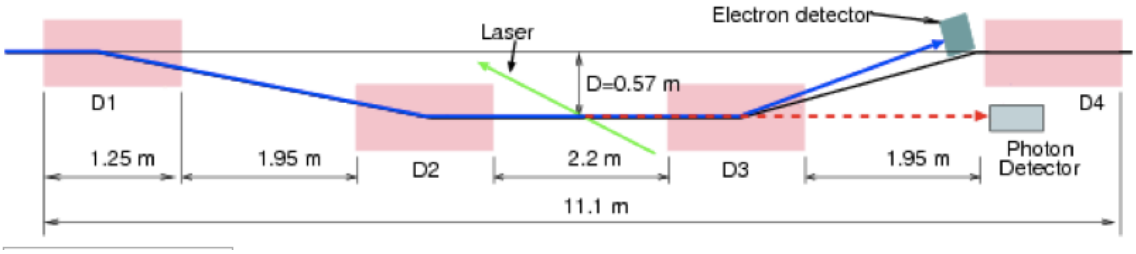

Figure (1): The Compton Polarimeter, consisting of four dipoles, an optical cavity (with a laser and two mirrors), a photon detector, and an electron detector [4]. The electron beam enters the polarimeter from the left in this picture

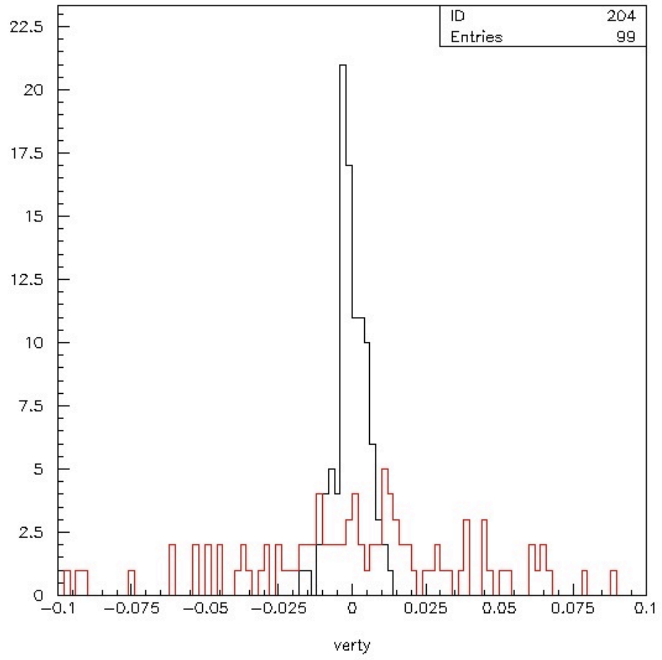

Figure (2): The y-position of the main beam (black) and the halo (red). This graph is not scaled by the luminosity; its purpose is to show that the halo is located mostly at the tails of the Gaussian of the main beam.

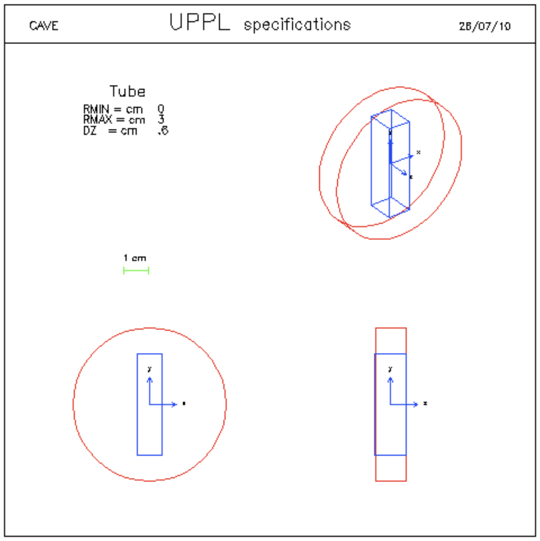

Figure (3): The cavity aperture. A metal disk was created first (red), and then a rectangular hole was created.

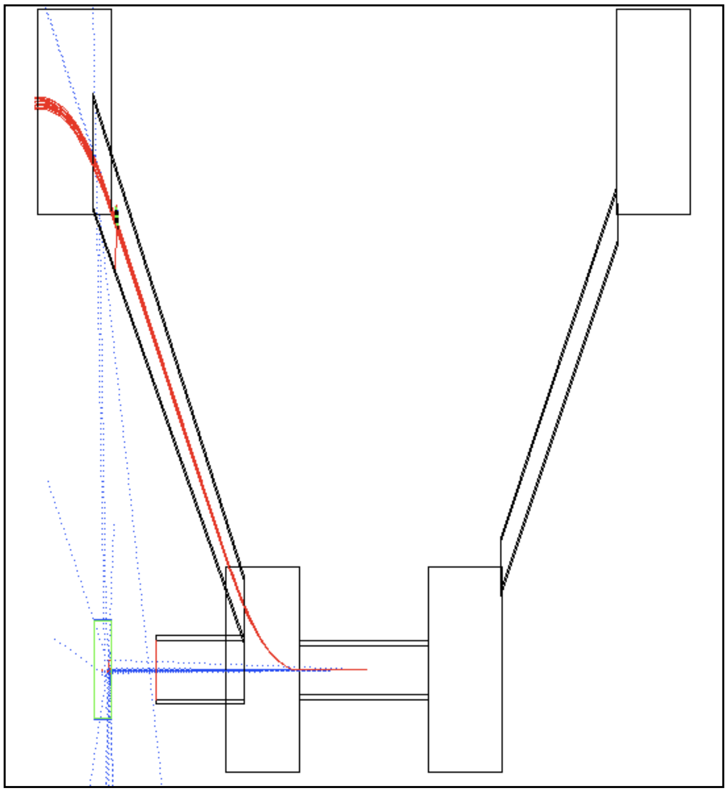

Figure (4): The simulation of the Compton Polarimeter with just backscattering events. The electron-beam enters the polarimeter from the right in this picture.

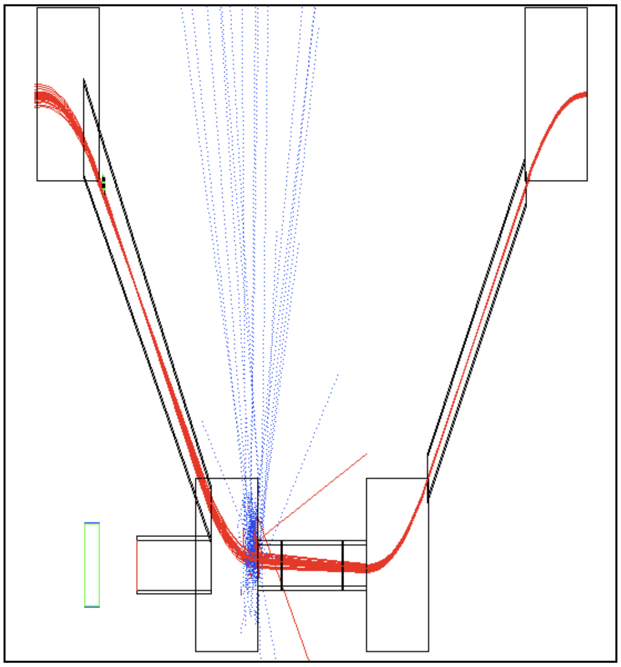

Figure (5): Simulation of the Compton Polarimeter with just the beam halo background radiation. This figure includes the apertures. The electron-beam enters from the right in this picture

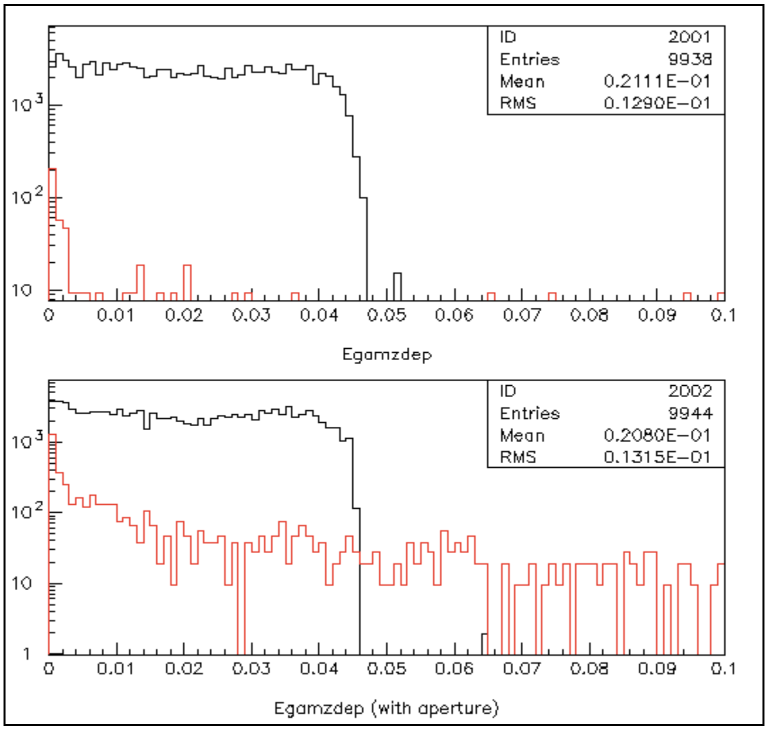

Figure (6): The energy distribution versus rates in the photon detector without the aperture (top) and with the aperture (bottom). The main beam is in black, the halo is in red.

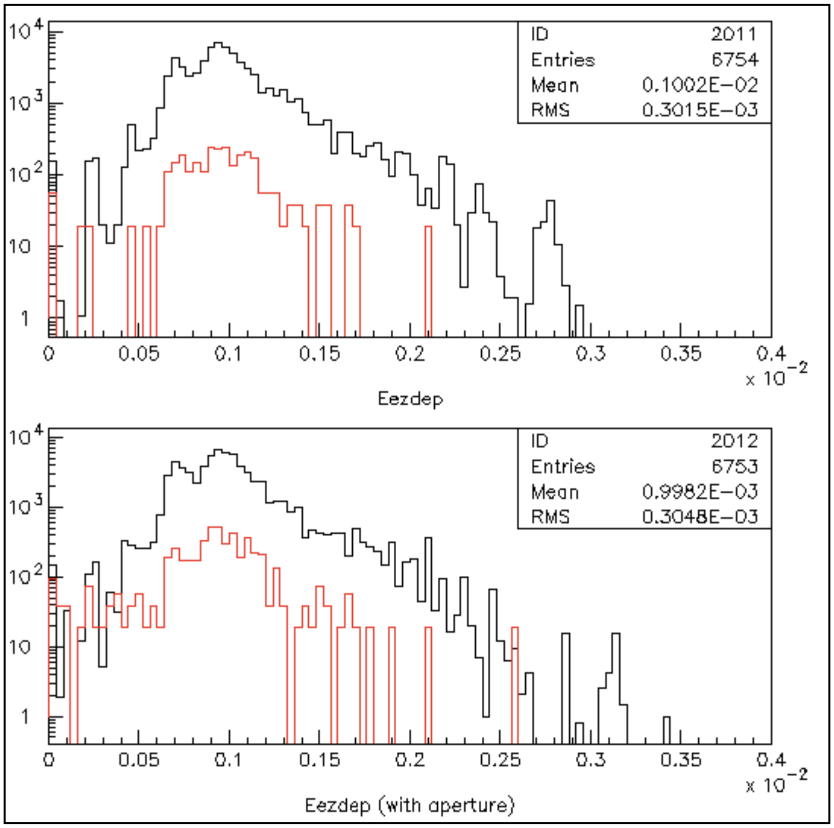

Figure (7): The energy distribution versus rates for the electron detector without the aperture (top) and with the aperture (bottom). The main beam is in black and the halo is in red.