

Optical Properties of Pion Detector for the Moller Experiment (I)

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Abstract

The optical response of the Cerenkov Lucite detector to pions and electrons in the energy range expected in the Moller experiment was studied using FLUKA Monte Carlo simulation tool.

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I Introduction

Moller experiment proposes to measure the parity-violating asymmetry in the scattering of longitudinally polarized 11 GeV electrons from the atomic electrons in a liquid hydrogen target [MOLLER 2012].

Nominal design parameters for the proposed measurement are shown in Table 1. While some of the design parameters could change at a few percentage level after further optimization of the design, possible changes will not be at the level to influence the scope and the results of this report.

Parameter	Value
E [GeV]	≈ 11.0
E' [GeV]	1.8 - 8.8
θ_{cm}	46° - 127°
θ_{lab}	0.23° - 1.1°
$\langle Q^2 \rangle$ [GeV^2]	0.0056
Maximum Current [μA]	85
Target Length (cm)	150
ρ_{tgt} [g/cm^3] (T= 20K, P = 35 psia)	0.0715
Max. Luminosity [$\text{cm}^{-2} \text{sec}^{-1}$]	$3.4 \cdot 10^{39}$
σ [μBarn]	≈ 40
Møller Rate [GHz]	≈ 135
Statistical Width(2 kHz flip) [ppm/pair]	≈ 83
Target Raster Size [mm]	5 x 5
ΔA_{raw} [ppb]	≈ 0.6
Background Fraction	≈ 0.08
P_{beam}	$\approx 85\%$
$\langle A_{pv} \rangle$ [ppb]	≈ 35
$\Delta A_{stat} / \langle A_{expt} \rangle$	2.1%
$\delta(\sin^2 \theta_W)_{stat}$	0.00026

Table 1. Nominal design parameters for the proposed Moller measurement [MOLLER 2012].

The schematics for the proposed experiment is shown in Figure 1 and an overview of the Moller experiment detector system is shown in Figure 2.

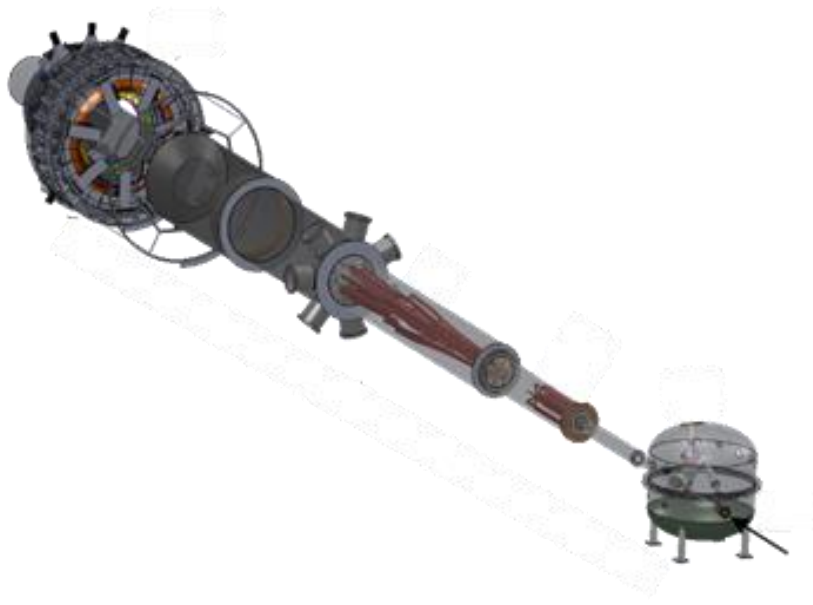


Figure 1. Schematics of the Moller experiment.

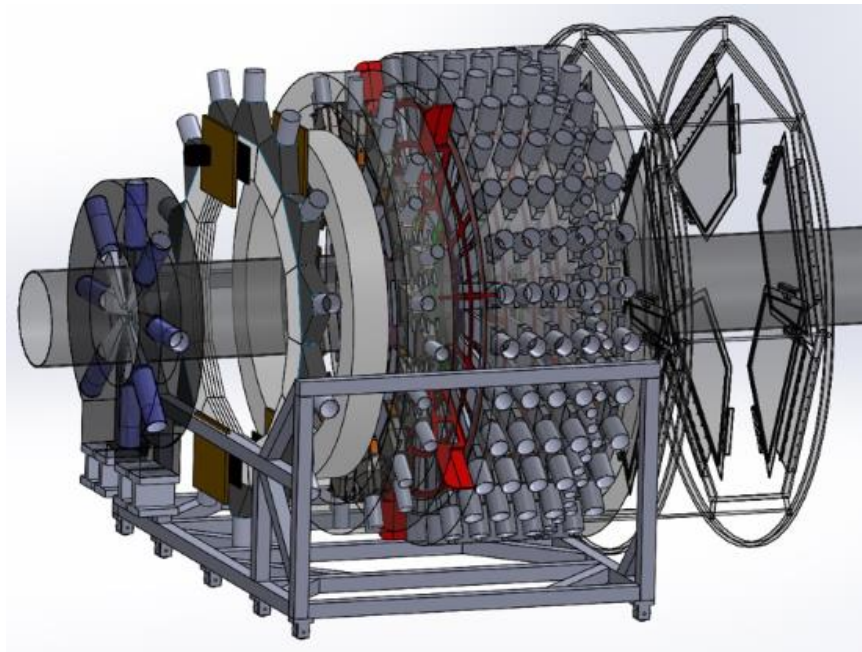


Figure 2. Schematics of the pion detector position in a relation to the position of the surrounding detectors.

The scope of this report is to calculate optical properties of the latest design of a acrylic pion detector, conceptually designed as shown in Figure 3 [ARMSTRONG 2021], for the detection of pions and electrons.

The results are obtained using a simulation tool called FLUKA [FERRARI 2005, BATTISTONI 2007], a fully integrated particle physics Monte Carlo simulation package with many applications in high energy experimental physics and engineering, shielding, detectors and telescopes design, cosmic ray studies, dosimetry, medical physics and radio-biology. Once the incoming particles are generated and the properties of the material are known, it is straight forward to simulate the detector properties. The physical mechanisms implemented in today's simulation software are very accurate and the differences between the simulated and measured results are in the most cases negligible.

- 20 cm thick Pb donut, no concrete
- 1" wide Acrylic detector in radial direction, 7 cm deep (z), 42 cm (azimuthal) located behind Pb donut
- 1" diameter PMT located behind acrylic; no light guide, no bevels
- Pb shielding at inner and outer radial edges: 30 kg/detector
- Still to optimize:
 - Pb shielding extent in Z
 - Acrylic depth in Z
 - Coupling of PMT, number of PMTs

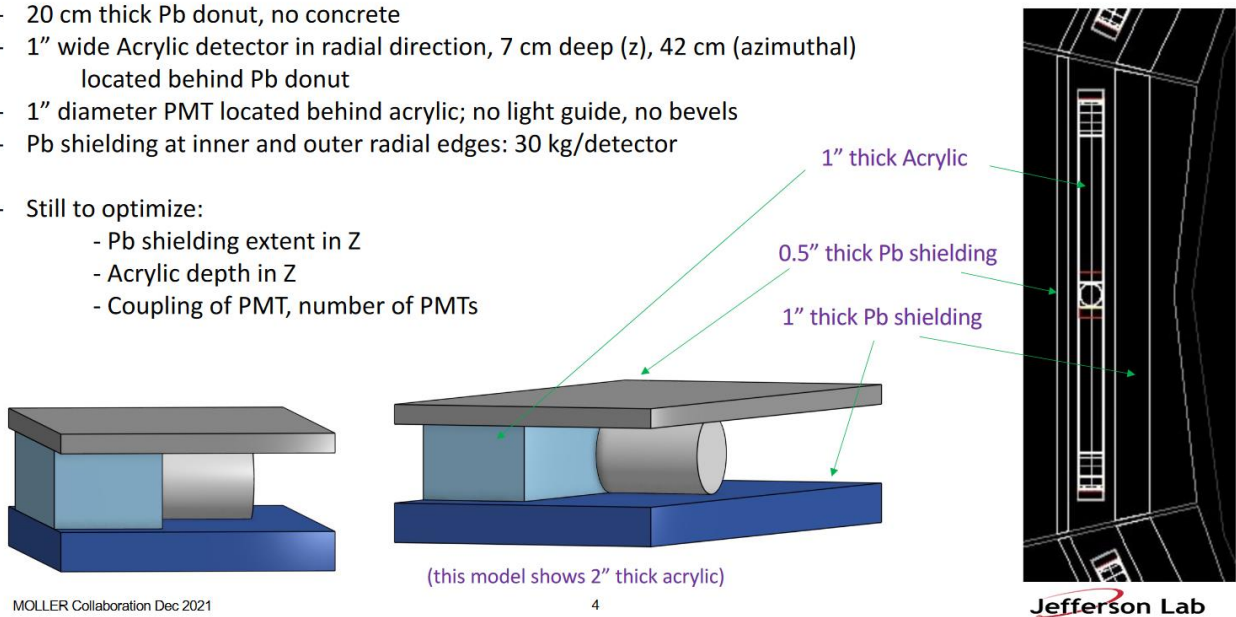


Figure 3. Dimensions of the proposed pion detector [ARMSTRONG 2021].

Since the accepted Moller scattered electrons have momentum range of ~ 2.75 to 7.9 GeV, detailed studies are performed for pions and electrons in this momentum range.

II Theoretical Performances of Cerenkov Lead Glass Calorimeter

For an Acrylic Cerenkov detector (index of refraction $n=1.49$) the kinetic energy threshold for electrons to produce optical photons is ~ 0.18 MeV and for pions ~ 49 MeV. For both particles the number of produced photons in the wavelength interval of 300 to 600 nm is shown in Figure 4 for 1 cm thick acrylic sheet. The Cerenkov angle is shown in Figure 5 for an energy of up to 1 GeV. For the momentum range of 2.75 to 7.9 GeV the generation of optical photons is essentially the same for pions and electrons.

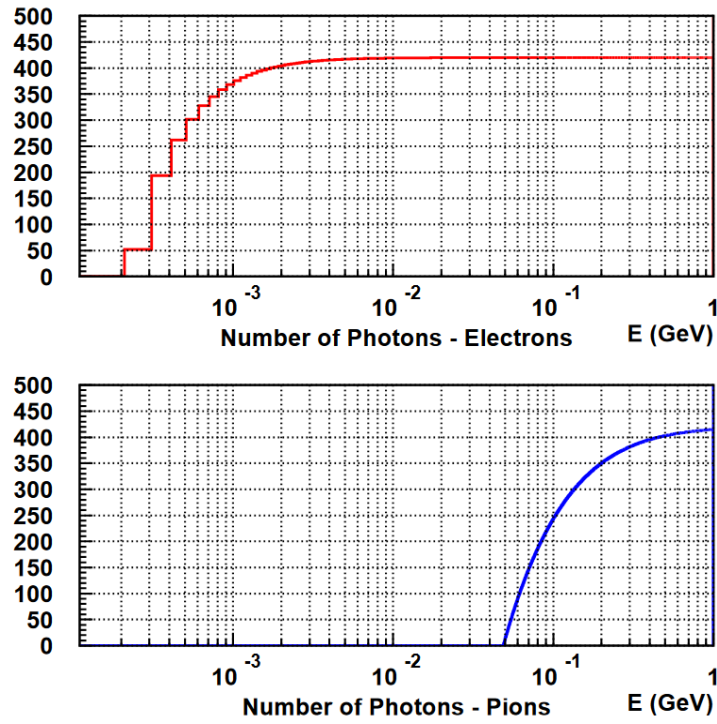


Figure 4. Number of photons in the wavelength interval of 300 to 600 nm for 1 cm thick acrylic sheet as a function of electron and pion energies.

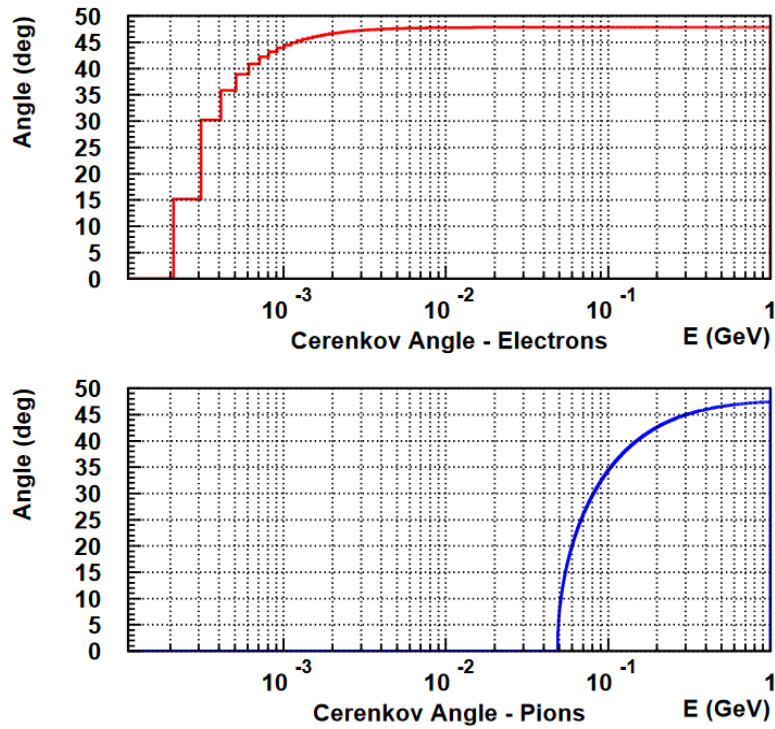


Figure 5. Cerenkov angle for the acrylic as a function of electron and pion energies.

III Testing FLUKA Optical Segment

FLUKA's optical photons production and propagation through the material was tested in our previous report [YCHEN 2018] on a 4 cm thick, 40 cm x 40 cm acrylic sheet. The wavelength sector for the optical photons was chosen in the region of sensitivity for most of the photomultiplier tubes between 300 nm and 650 nm. We compared number of photons produced by 0.1, 1 and 5 GeV pions to the expected theoretical values. The example of the optics for 4 cm thick acrylic is shown in Figure 6. In this report we primarily study 7 cm thick acrylic. The results for 7 cm thick acrylic are shown in Table 2. From the results in the table we concluded that both the creation and propagation of optical photons are consistently calculated in FLUKA. The small difference in the number of photons can be attributed to pion reaction in the acrylic sheet. For 0.1 GeV pions Cerenkov angle is below the acrylic critical angle, therefore the optical photons refract. For the 1 GeV and above, the Cerenkov angle is above the acrylic critical angle, therefore the optical photons reflect.

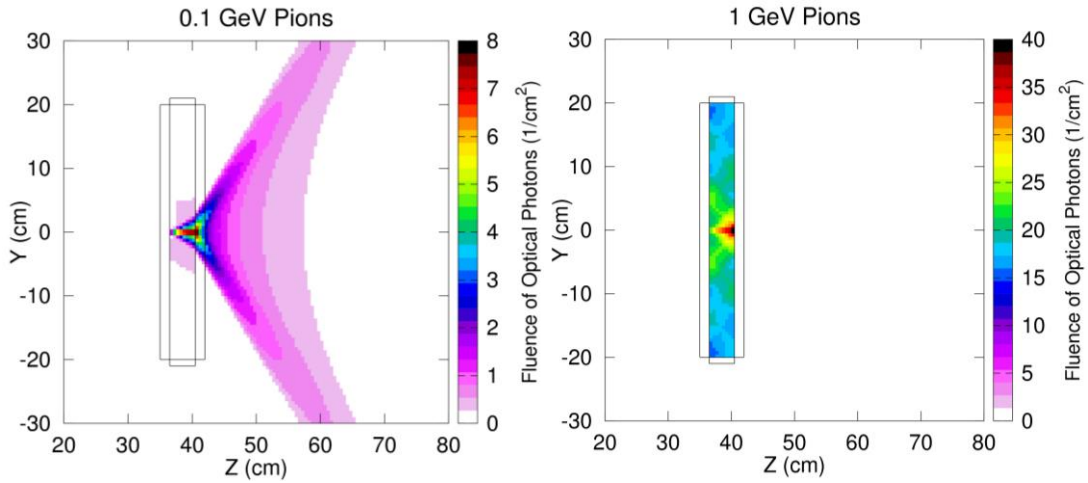


Figure 6. Cerenkov light production and propagation in a 4 cm thick Lucite.

Theoretical Number of Optical Photons (300 nm – 650 nm, 7 cm thick Acrylic)		
Kinetic Energy	Electrons	Pions
0.1 GeV	3166	1833
1 GeV	3166	3126
5 GeV	3166	3164

FLUKA Number of Optical Photons (300 nm – 650 nm, 7 cm thick Acrylic)			
Kinetic Energy	Pions (no EM secondaries)	Pions (with EM secondaries)	Electrons
0.1 GeV	1906	2024	5051
1 GeV	4490	4672	5656
5 GeV	4557	4909	5960

Table 2. Comparison of the number of FLUKA's produced optical photons to the theoretical expectation.

IV Properties of the Acrylic Cerenkov Calorimeter

In this chapter we report the results from the study of properties of the detector shown in Figure 3. The study is performed for the pion and electron momentum of $3.5 \text{ GeV}/c^2$, the mean momentum of the Moller electrons momentum. An example of Cerenkov light production and propagation in the acrylic is shown in Figure 7 for the pion beam in the center of the detector and displaced by 10 cm from the detector center. Figure 8 shows the number of Cerenkov photons striking the photomultiplier tube as a function of the pion position along the Pion Detector assuming that the photomultiplier is positioned in the center of the detector as shown in Figure 3.

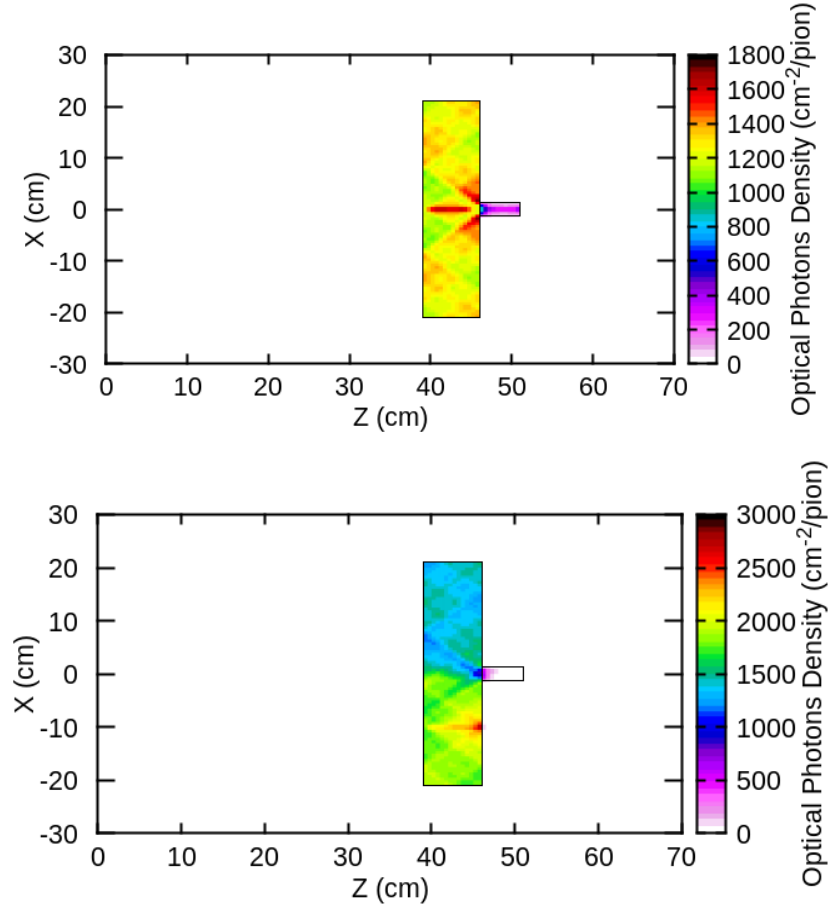


Figure 7. Cerenkov light production and propagation in the plane normal to the beam axis for the pion beam in the center of the detector and displaced by 10 cm from the detector center.

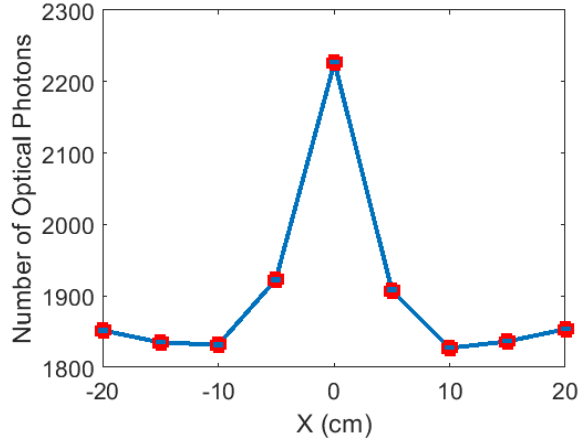


Figure 8. Number of Cerenkov photons striking the phototube as a function of the pion position along the detector.

Same study is repeated for the electron beam. The Cerenkov light production and propagation in the acrylic for electrons is undistinguishable from the production and propagation for pions shown in Figure 7. The total number of Cerenkov photons striking the photomultiplier tube as a function of the electron position along the Pion Detector is shown in Figure 9.

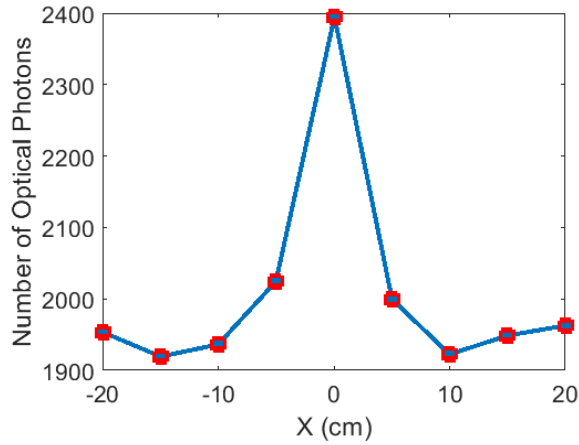


Figure 9. Number of Cerenkov photons striking the phototube as a function of the electron position along the detector.

The total number of Cerenkov photons striking the photomultiplier tube was also studied as a function of the detector thickness. An example of Cerenkov light production and propagation in the acrylic is shown in Figure 10 for detector thicknesses of 7 cm, 5 cm and 2 cm, for the pion beam displaced by 10 cm from the detector center. The total number of Cerenkov photons striking the photomultiplier tube as a function of detector thickness is shown in Figure 11.

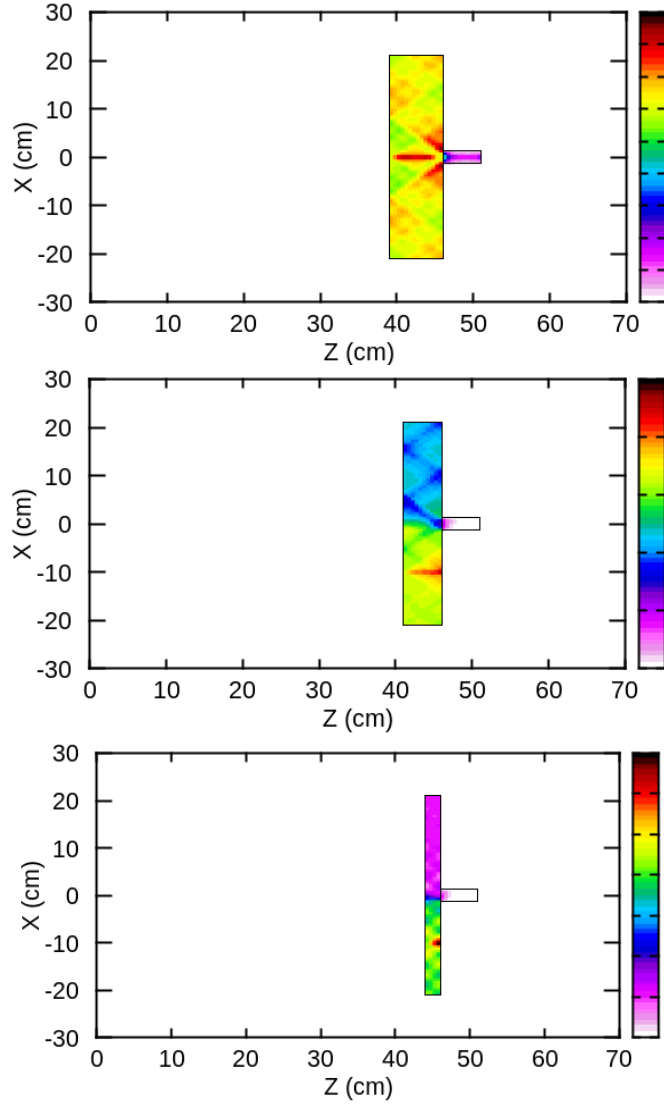


Figure 10. Cerenkov light production and propagation in the plane normal to the beam axis for the pion beam displaced by 10 cm from the detector center for thicknesses of 7, 5 and 2 cm.

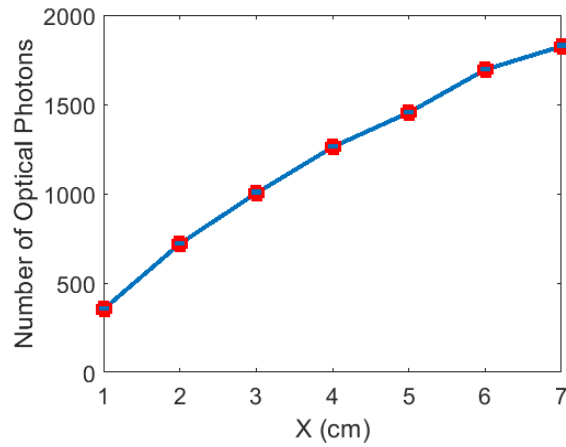


Figure 11. Number of Cerenkov photons striking the phototube as a function of the detector thickness for the pion beam displaced by 10 cm from the detector center.

An example of Cerenkov light production and propagation in the acrylic is shown in Figure 12 for detector thicknesses of 7 cm, 5 cm and 2 cm, for the pion beam striking the entire area of the detector. For this case, the total number of Cerenkov photons striking the photomultiplier tube as a function of detector thickness is shown in Figure 13.

Examining the Figure 12 one notices that the detector efficiency is very position dependent. Comparing Figure 11 and 13 we see that the number of optical photons hitting the photomultiplier is about the same.

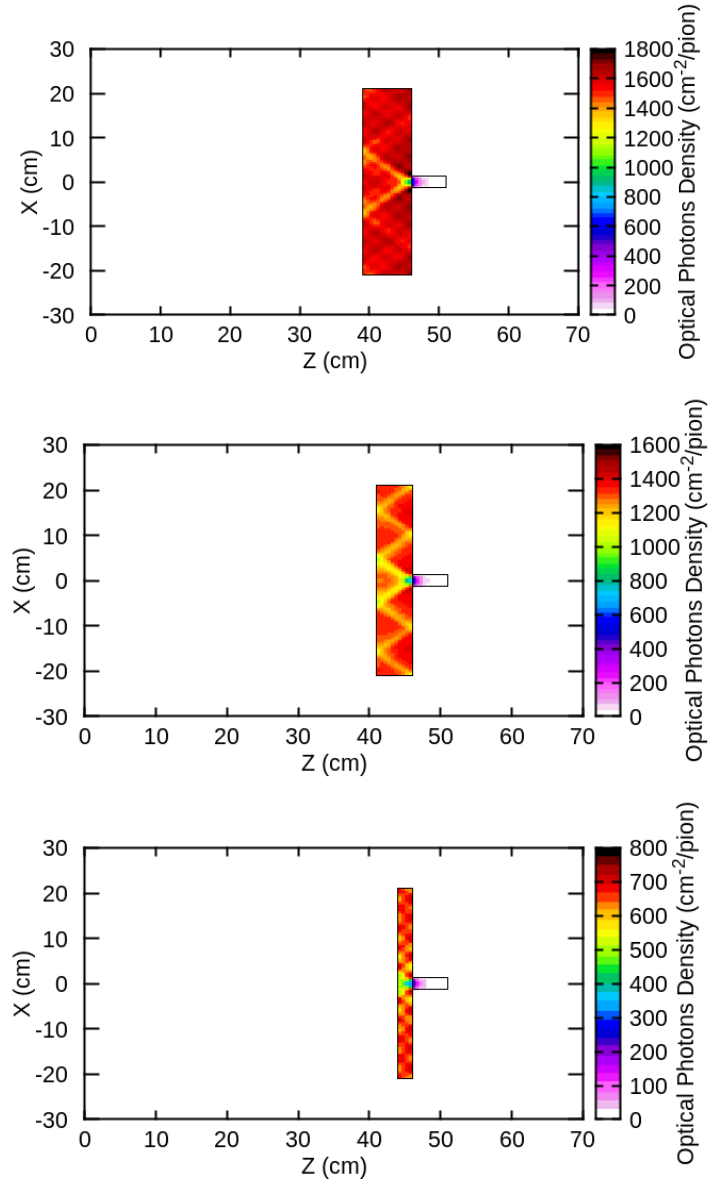


Figure 12. Cerenkov light production and propagation in the plane normal to the beam axis for the pion beam distributed along the detector surface for thicknesses of 7, 5 and 2 cm.

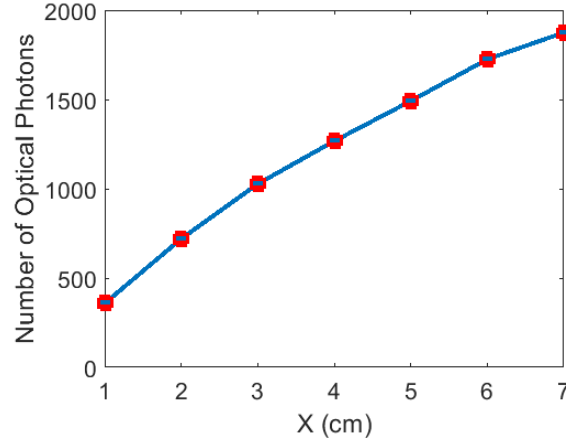


Figure 13. Number of Cerenkov photons striking the phototube as a function of the detector thickness for the pion beam distributed along the detector surface.

For this level of simple testing, introducing the top and bottom lead shielding does not change the number of optical photons. The deposited energy for such a system is shown in Figure 14. Introducing lead donut as expected changes the number of optical photons by factor of ~ 2.5 . The deposited energy for such a system is shown in Figure 15.

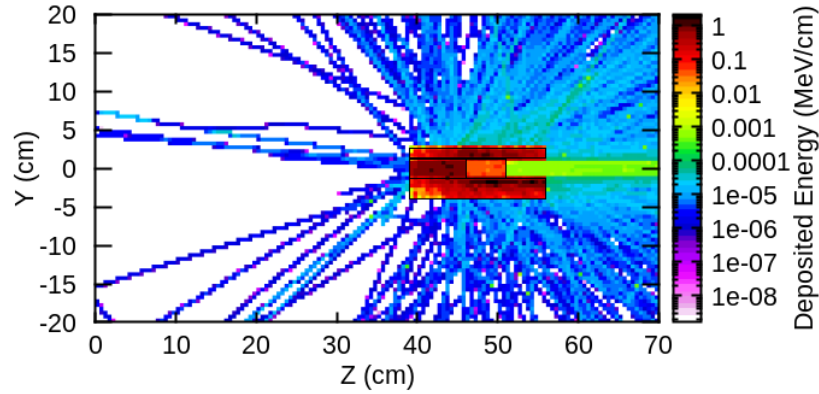


Figure 14. Deposited energy for the pion beam distributed along the detector surface.

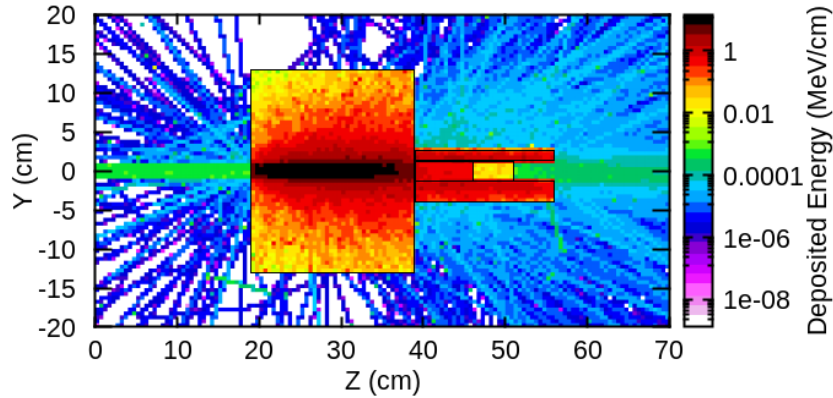


Figure 15. Deposited energy for the uniformly distributed pion beam of the momentum of $3.5 \text{ GeV}/c^2$.

VI Summary and Conclusion

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