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Analysis of Radiation Damage in Lead Glass

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1 Introduction

The RADPHI experiment indicated that radiation damage over time reduces the light output of F8 lead glass (Figure 1), which severely hinders the energy resolution [1]. The GlueX Forward calorimeter (FCAL) will receive similar dosage. To avoid this loss in energy resolution, radiation hard lead glass (RHG) will be used. The analysis in this paper attempts to determine the optimal amount of RHG to be used and consists of four steps:

- Conduct an electromagnetic background simulation to determine the expected amount of radiation dosage within the GlueX FCAL.
- Damage standard F8 lead glass at Indiana University Center for Exploration of Energy and Matter (IUCEEM) with 20 MeV electrons; then measure the effect of radiation damage on the transmission through the lead glass.
- Develop a radiation damage model using the data above and insert it into HDGEANT.
- Run simulations with the damage model inserted to predict the degradation in energy resolution of the FCAL.

2 Simulating Electromagnetic Background

To determine the loss of energy resolution over time for the FCAL, the effect of the electromagnetic background on the FCAL must be calculated. Simulations calculated the energy deposited in $1\,\text{cm} \times 1\,\text{cm} \times 1\,\text{cm}$ volumes. Figure 2 shows data from this simulation. The figure shows a slice 2 cm into the FCAL along the 45 cm length (z) of the block. The units are kRad per year per rate of photons exiting the radiator in GHz. The blocks nearest the center of the FCAL receive about 10 kRad per year (10^7 s running per year) per photons on target of 10^8 Hz. The dosage for a single radius varies as a function of depth. It is highest in the front end of the block, the z position nearest the radiator, and drops off down the block (away from the radiator).

3 Damaging the Blocks

The standard blocks are made of F8 lead glass with dimensions of $4\,\text{cm} \times 4\,\text{cm} \times 45\,\text{cm}$. A linear accelerator dosed sections of lead glass blocks with electrons with an energy of 20 MeV. The area dosed was a $2.5\,\text{cm} \times 2.4\,\text{cm}$ area on the edge perpendicular to z of the block. This was done so multiple doses could be given to a single block (See Figure 3). The linear accelerator was calibrated to a number of kRad per dose, see Appendix A. The blocks were slightly radioactive at the end of the dosing so they were given a few days to cool.

The transmission of light through the blocks as a function of wavelength was measured using a spectrophotometer, see Figure 4. The spectrophotometer was set up so the transmission through damaged areas

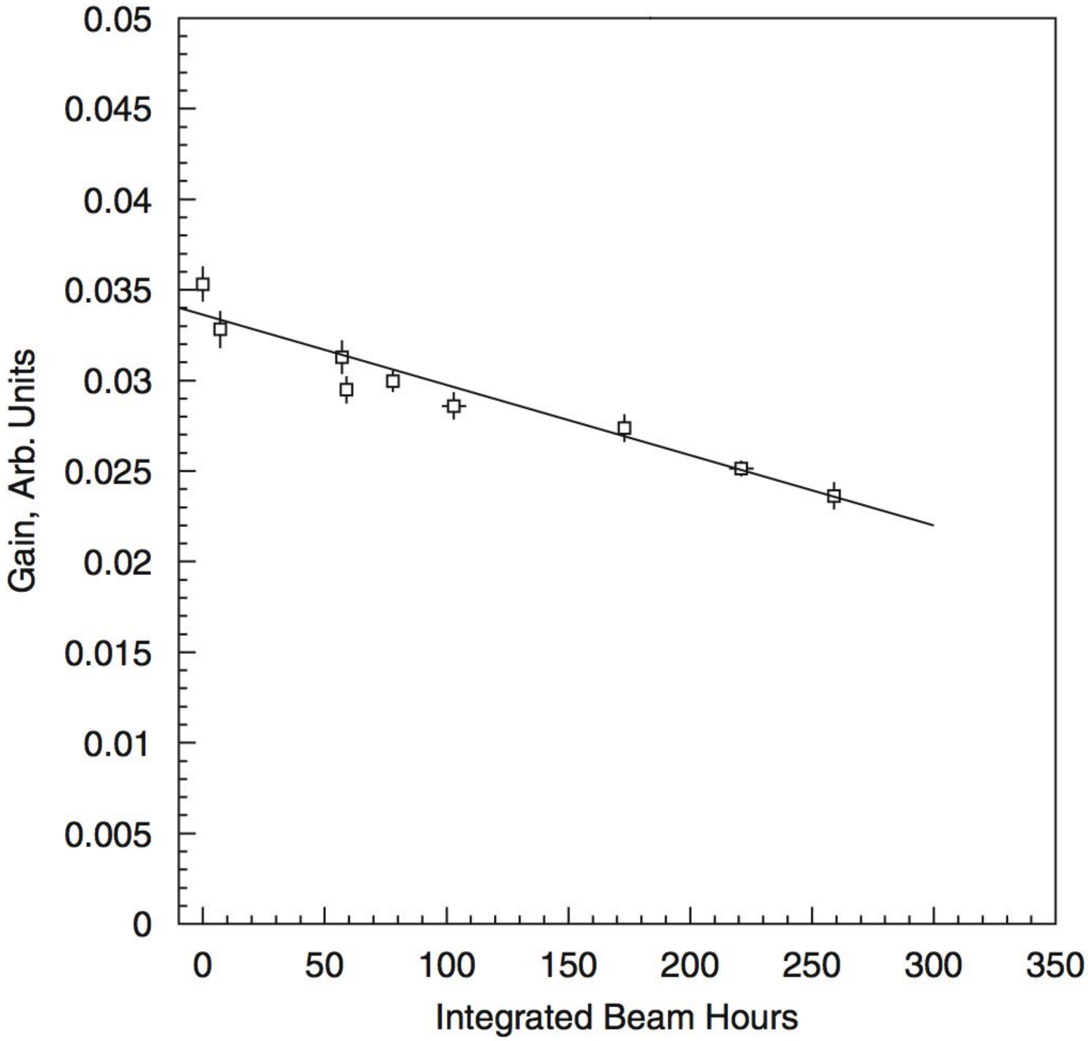

Figure 1: The gain over time of the PMTs used in the RADPHI calorimeter.

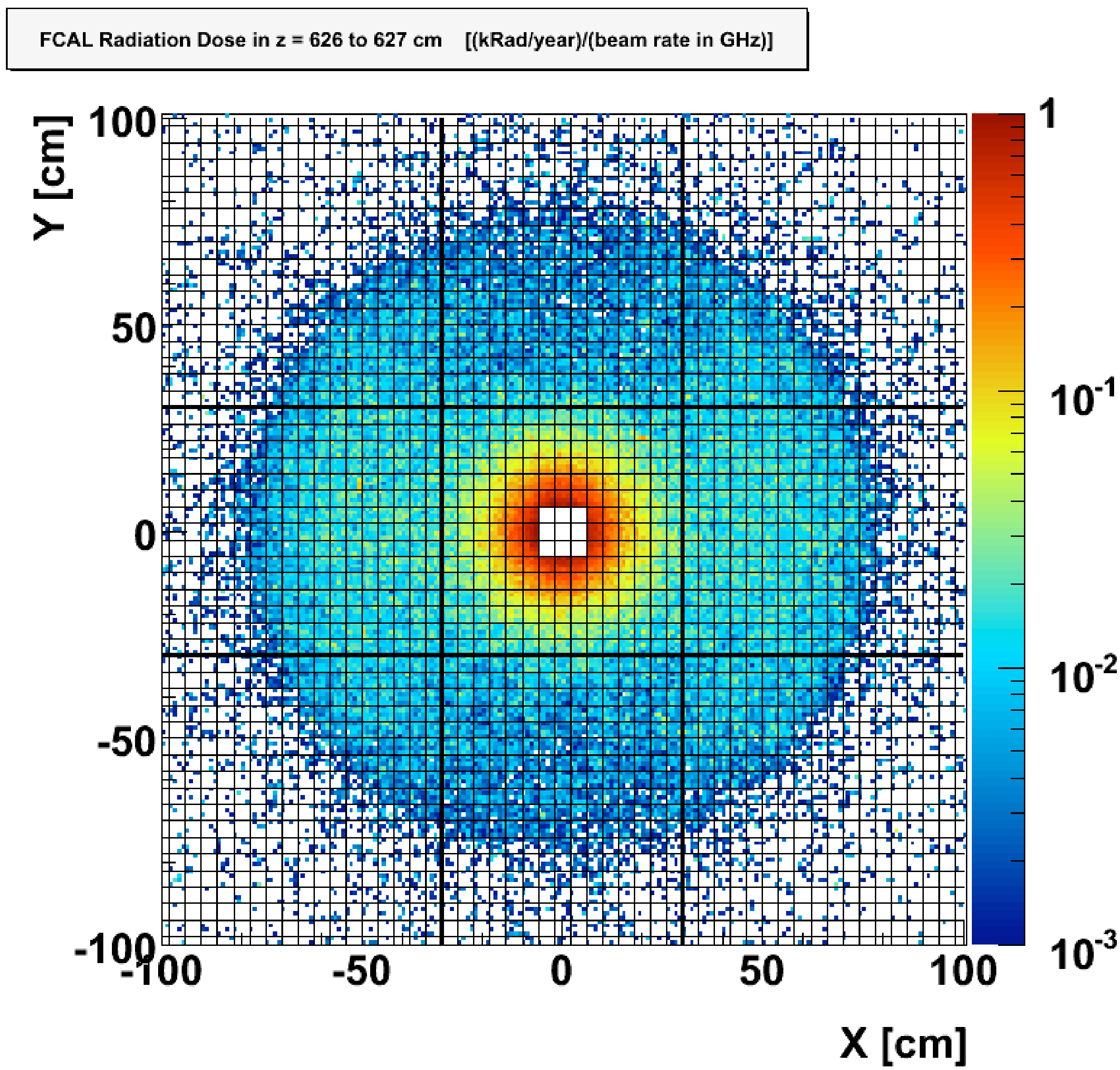

Figure 2: HDGEANT simulation of expected dosage in the FCAL. The units are kRad per year per rate of photons exiting the radiator in GHz. This figure in particular is a 1 cm slice in z; 2 cm into the 45 cm (z) length of the block.

could be measured individually. Reflections occurred within the spectrophotometer and therefore were taken into account for all of the following data. The data shown in Figure 5 is rearranged so that transmission is a function of dosage and each curve is for a different wavelength of light. The data points are fit to Equation 1,

$$T = A \cdot exp(B \cdot Dose(kRad)) + C, \tag{1}$$

where A, B, and C are free parameters.

The radiation distribution within the block is important in determining damage in a segment. GEANT4 was used to show the energy deposition from the 20 MeV electron dosed blocks as a function of depth, see Figure 6. Most of the energy from 20 MeV electrons is deposited in the first fourteen millimeters, where it is assumed all of the transmission loss occurs. This is why Equation 1 is assumed to be valid over 1.4 cm. The energy deposition is also symmetric around seven millimeters of depth. Assume the form:

$$T_1^2 = T, \tag{2}$$

where T_1 and T are the transmissions of light through the block in 7 mm and 14 mm respectively.

Because of this assumption we can now use Equation 3 to get the transmission percentage as a function of dosage in seven millimeters of lead glass:

$$T_1 = \sqrt{A \cdot exp(B \cdot Dose(kRad)) + C} \tag{3}$$

where A, B, and C are the fit values from $Figure$ 5. The loss in transmission through the block can be represented by the transmission with damage divided by the transmission with no damage, see Equation 4.

$$F = \frac{T_{\text{eff}}}{T_0} \tag{4}$$

The effective transmission, T_{eff}, after a particular dose is represented by Equation 5. T_{eff} takes into account the changing importance of different wavelengths of light as the blocks become damaged. T_0 is Equation 5 with the dosage set to zero.

$$T_{\text{eff}}(z_0, R, t) = \sum_{\lambda} \prod_{z=z_0}^{z_f} T_\lambda(z, Dosage(R, t))\epsilon(\lambda)n(\lambda) \tag{5}$$

T_λ is the transmission through a 7mm slice with some dosage in kRad and indexed by a particular wavelength. The dosage is a function of depth in the block (z), position in the FCAL (R), and time spent running (t) which is taken from the electromagnetic background simulation, see Figure 2. The total transmission of light through the block is determined from using the starting position (z_0) of the interaction and multiplying the transmission values successively down to the end of the block. For example, if the interaction starts 17 cm into the block, there will be 40 slices of 7 mm multiplied together. Each slice uses a unique dosage that is dependent on the z position within the block, the radial location of the block within the FCAL, and the time running of GlueX. $\epsilon(\lambda)$ is the quantum efficiency and is taken from Figure 7. $n(\lambda)$ is the distribution of Cherenkov photons modeled by Equation 6.

$$n_{\text{Cherenkov}} \propto \frac{1}{\lambda^2} \tag{6}$$

Each of these is a function of wavelength so each piece is multiplied together and then summed over wavelengths from 300 nm to 700 nm to get the effective transmission of Cherenkov light through the block that will be detected by the PMT. F is the ratio of Equation 5 divided by the same equation with the damage set to 0. Figure 8 shows F plotted as a function of distance to the end of the block for a block located at a radius of 20 cm within the FCAL. Each line represents a different duration of time running at 10^8 Hz. Figure 9 shows F as a function of distance through the block for various radii after 5 years of running.

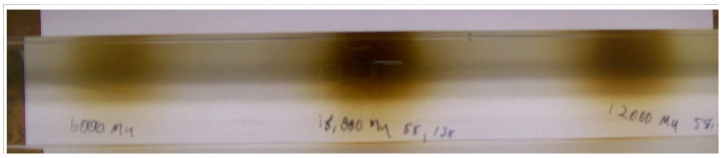

Figure 3: Standard F8 lead glass blocks after 20MeV electron dosage with a beam direction from the top. Dosages are about 300, 700, and 500 kRad left to right.

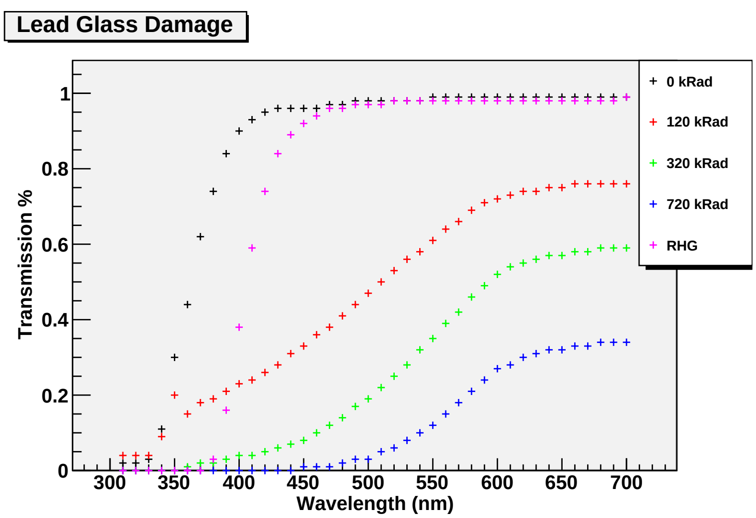

Figure 4: Spectrophotometer data of the regular lead glass, with and without damage, and the radiation hard glass.

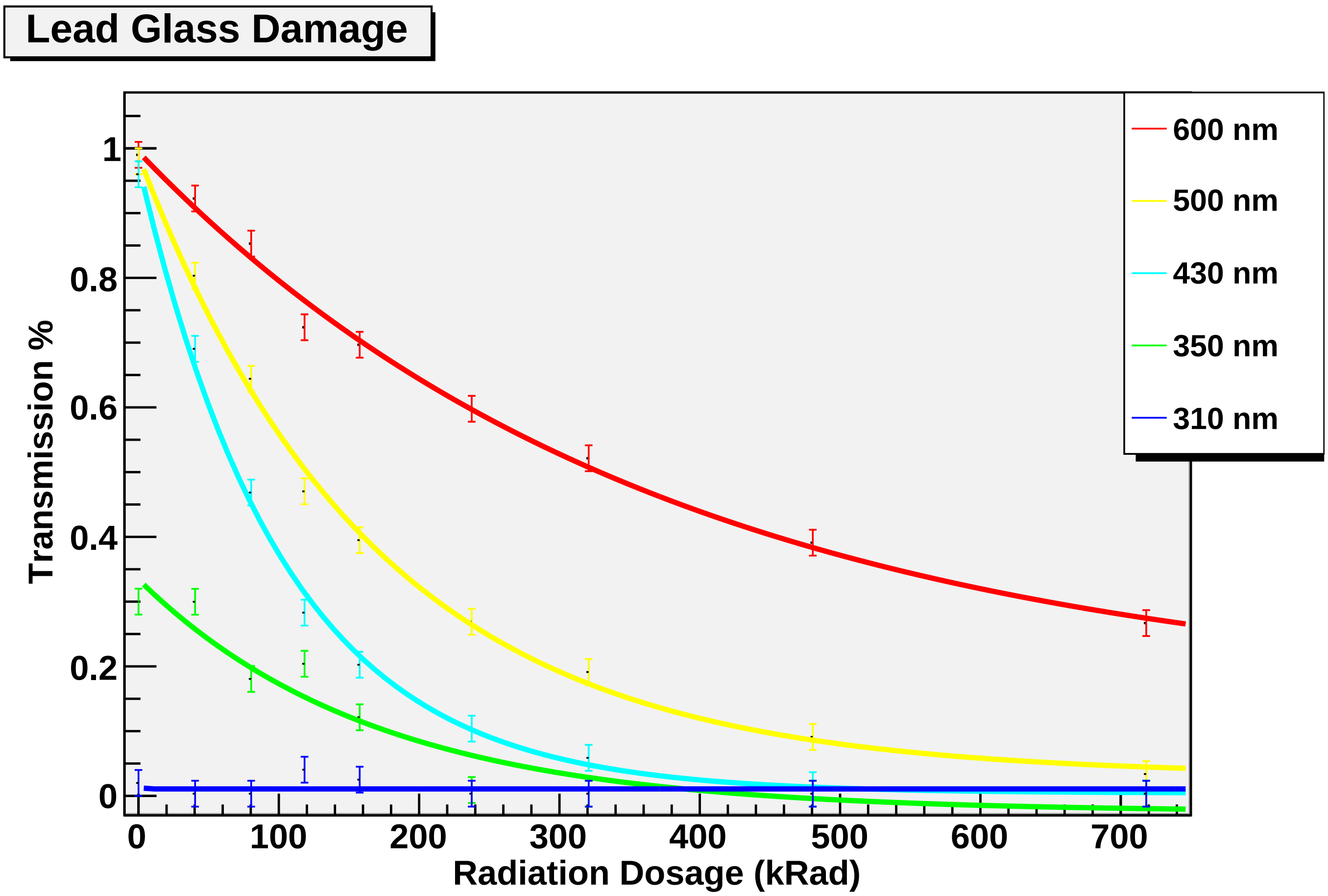

Figure 5: Transmission in block vs. dosage in kRad, fit to Equation 1. Each line is a different wavelength of light. Five different wavelengths are shown in the figure. In the analysis wavelengths from 700 nm to 300 nm were used.

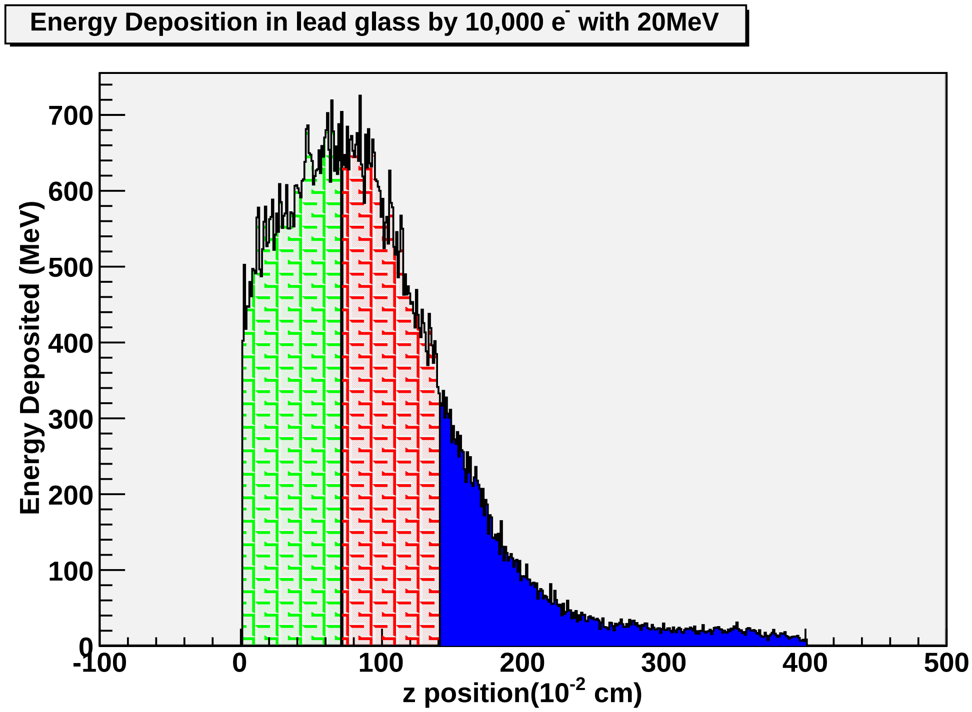

Figure 6: GEANT4 simulation of energy deposition of 20 MeV electrons as a function of depth in a 2.4 cm × 2.5 cm × 4 cm volume of lead glass. Notice almost all of the energy is in the first 1.4 cm. Also, the first half deposition is roughly symmetric about 7 mm of depth.

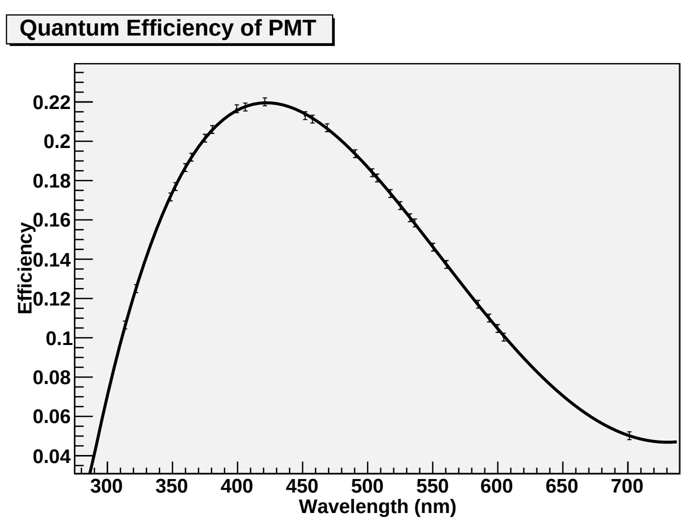

Figure 7: Quantum efficiency of the photomultiplier tube used by the FCAL.

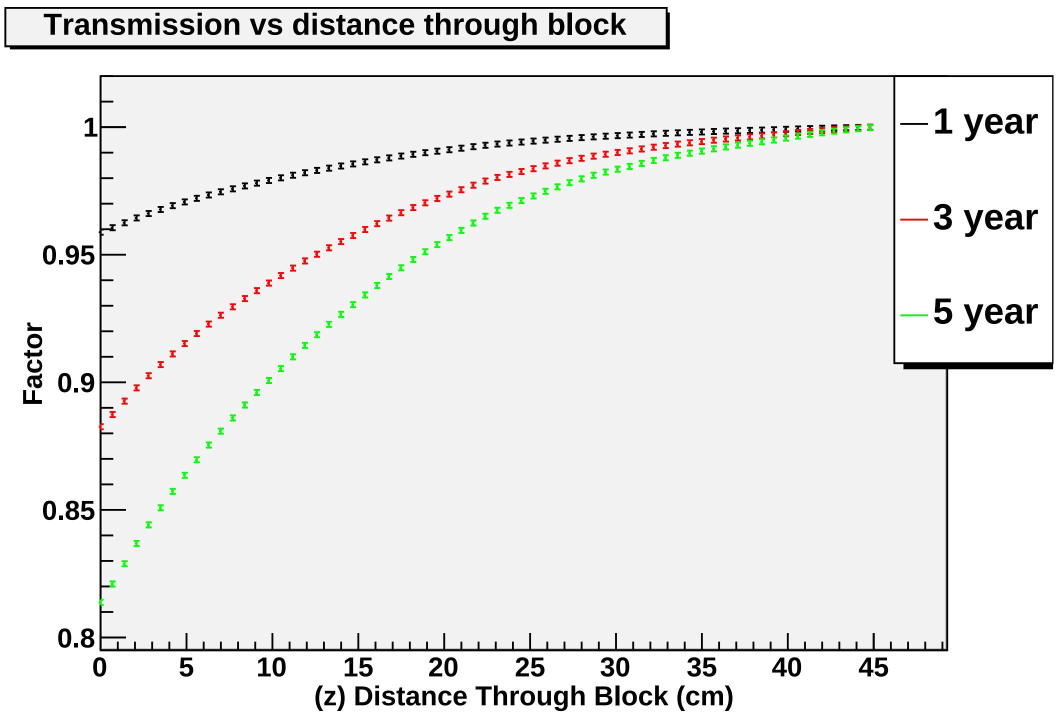

Figure 8: Transmission ratio (or Factor) after various years of running at an FCAL radius of 20 cm as a function of starting position in a regular lead glass block.

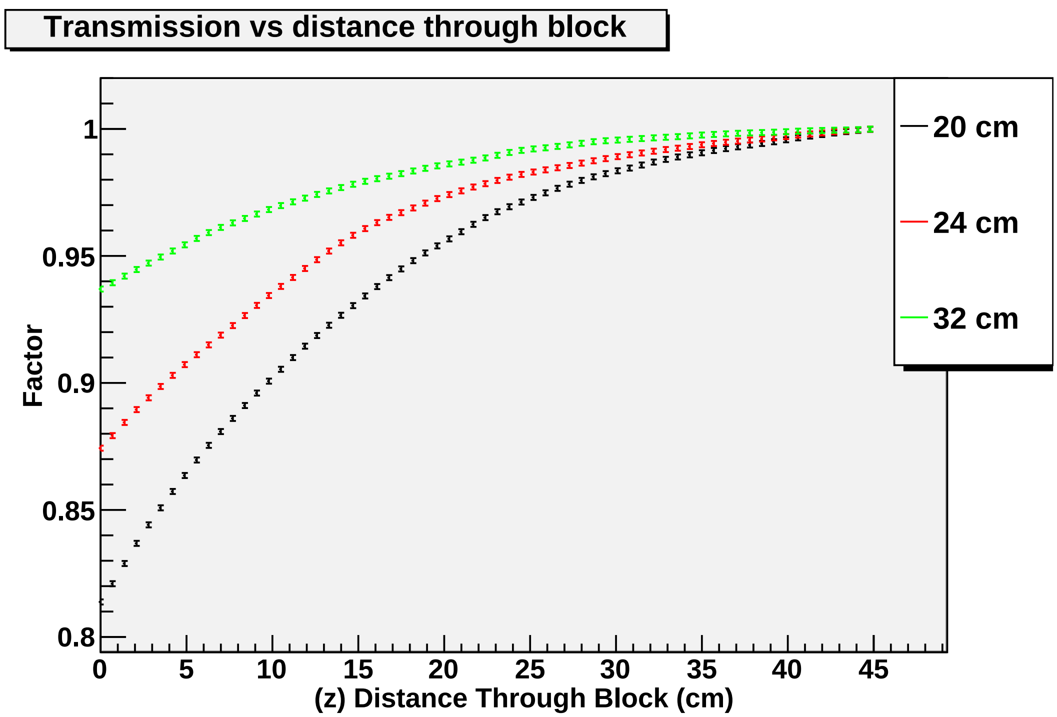

Figure 9: Factor after 5 years of running at various FCAL radii as a function of starting position in a regular lead glass block.

4 Inserting Damage into HDGEANT

The simulations will be performed using HDGEANT. The standard method for photon energy deposition uses the attenuation length of lead glass to account for the Cherenkov photons in a lead block by using Equation 7.

$$E_{final} = E_{initial} \cdot e^{-z_0/\lambda}, \tag{7}$$

where z is the distance from the end of the block along the 45 cm edge and λ is the attenuation length (100 cm). The model inserts the radiation damage into the simulation by multiplying F from Equation 4 with the exponential in Equation 7.

5 HDGEANT Simulation with Damage

Using a beam rate of 10^8 Hz and one year of running (10^7 seconds), several simulations were done. The RHG energy resolution was determined using GEANT4, see Appendix B. To optimize the energy resolution for a particular amount of damage, the non-linear correction as described by [2] was performed on each data set (different radii, different duration). As Figure 2 shows, the amount of radiation received is largely dependent on the radial position of the lead glass block. For one year of running time, Figure 10 shows the ratios of energy resolution of damaged glass to undamaged glass. Each curve corresponds to lead glass at a different radius. The RHG curve is the ratio of the RHG to undamaged regular glass for comparison. As the figure shows, none of the analyzed blocks becomes damaged enough to have the same energy resolution as undamaged RHG.

Figure 11 shows the energy resolution after three years of running. After three years a blocks with radius of 20 cm is almost to the break-even point. Figure 12 is after five years of running with blocks around 24 cm having the same energy resolution as RHG. The spectrophotometer had a rather large error associated with its measurements. Each spectrophotometer data point had an error of 3% that was found by measuring multiple times. The data points were fit to Equation 1 and the error on the fit was 1.2%. Figure 13 is the same as Figure 12 except the light colored lines are after the transmission has been decreased by 1.2% per slice to account for the error of the spectrophotometer.

6 Other Considerations

Several things to consider when making a conclusion are the validity of this analysis, time dependent energy resolution, and the ability to reconstruct a shower properly. To see if the analysis is valid, it was compared to work by Inyakin [3]. Inyakin damaged F8 lead glass with 70 GeV protons and compared the transmission before and after. The summary of the comparison between this method and Inyakin's is in Appendix C. The comparison showed substantial disagreement between the results. This is alarming until you consider the possibility that the affects of damage due to electrons differs from that of protons. This makes sense because of the two different dominant processes in which they interact in the matter. Work by Kobayashi [4] reports that for a resulting transmission that is 97% of the original 2400 kRad of dosage from protons would be required. Kobayashi also experimented with photons and the same crystal [5]. Kobayashi found that it would take over two orders of magnitude more dosage with photons to get to the same 97% transmission ratio. Another work by Kobayashi sees less of a difference in transmission lost between proton and photon damage in another type of crystal [6]. These works find a difference in the damaging effects of photons to protons and this difference varies by material. For example, a 97% transmission ratio for lead glass would require about 10^9 protons with an energy of 70 GeV. To get the same transmission loss from the model developed using electrons, electrons would need to deposit an order of magnitude more energy in the material than what was measured. Assuming electron damage is similar to photon damage, the apparent disagreement between our method and Inyakin is consistent with the Kobayashi's results that show the radiation dosage from different particles affect the material differently.

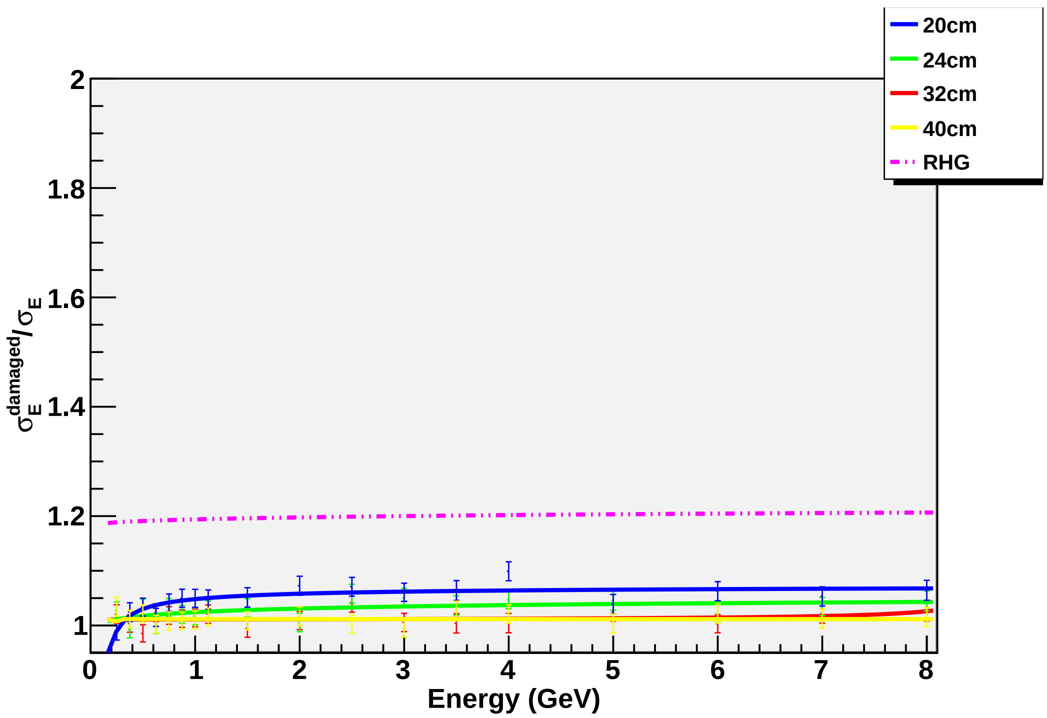

Figure 10: Ratios of energy resolution of damaged glass to undamaged glass for various radii. All curves are after one year of running with a beam rate of 10^8 Hz. The RHG curve is the ratio of undamaged radiation hardened glass and undamaged regular F8 lead glass.

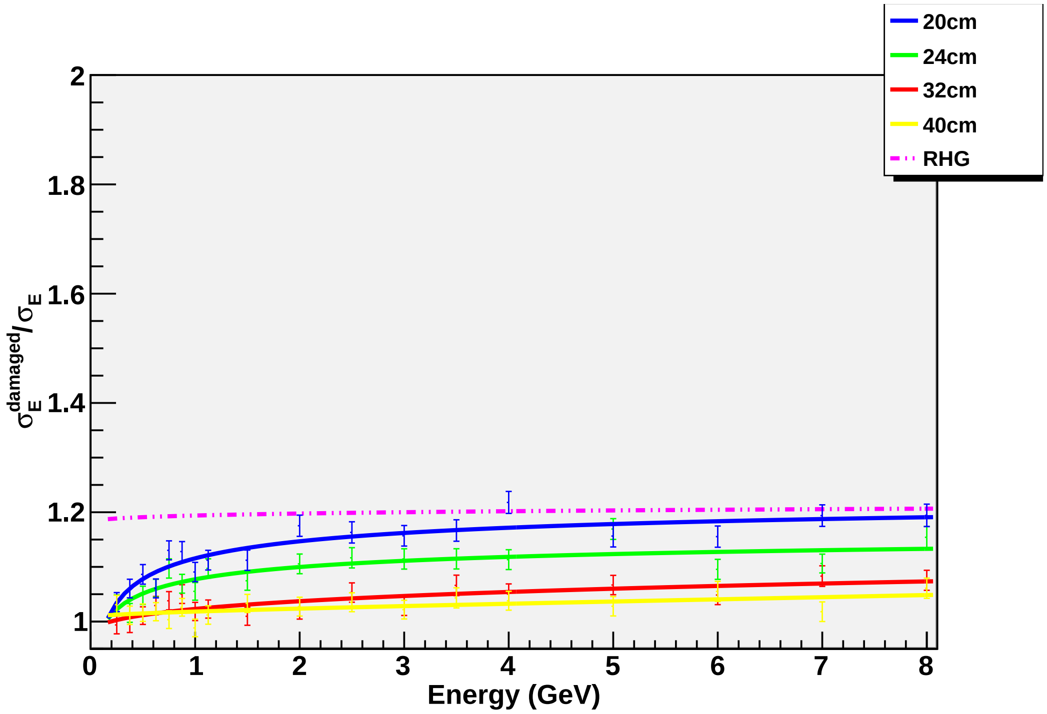

Figure 11: Ratios of energy resolutions after 3 years of running at 10^8 Hz.

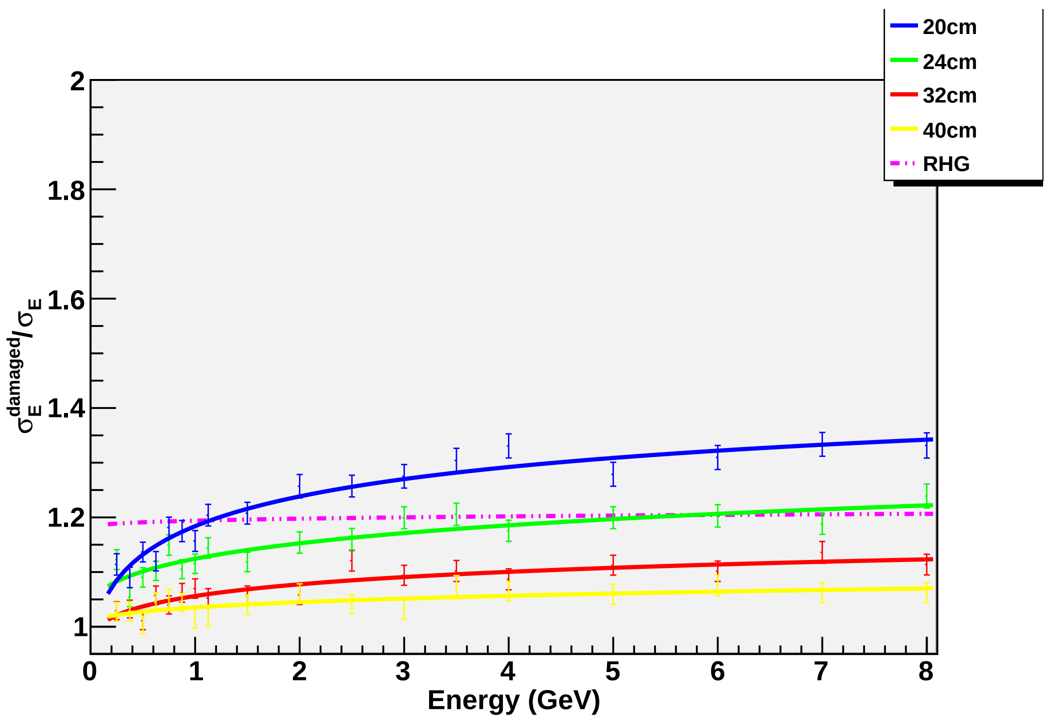

Figure 12: Ratios of energy resolutions after 5 years of running at 10^8 Hz.

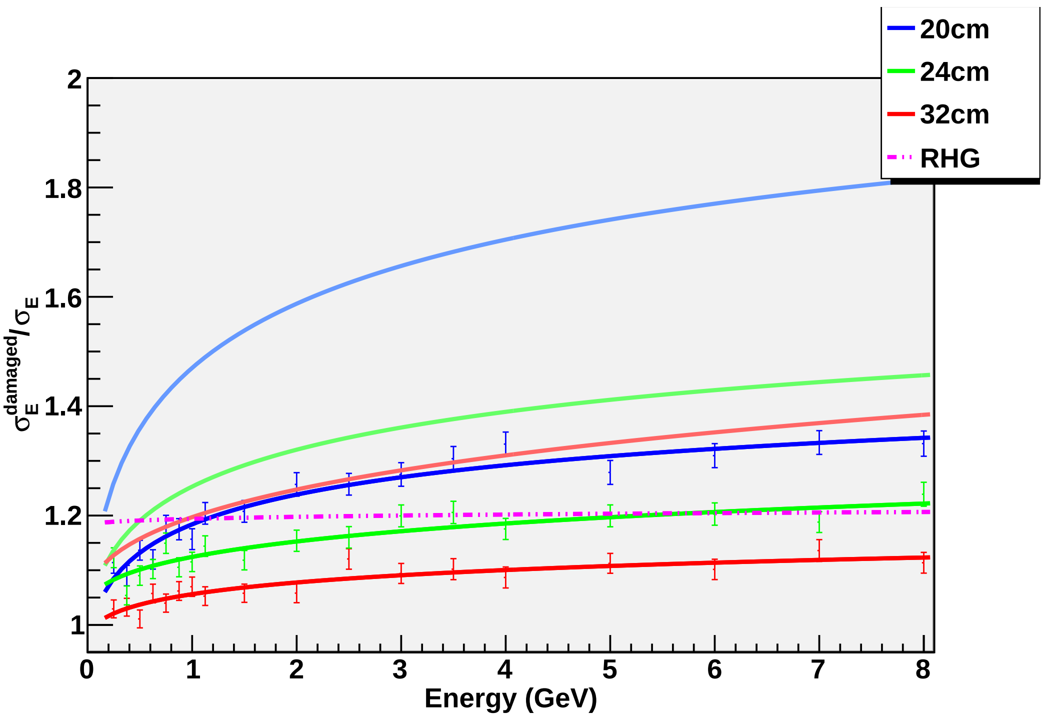

Figure 13: Ratios of energy resolutions after 5 years of running at 10^8 Hz. The lighter color lines are with 1.2% worse transmission per slice.

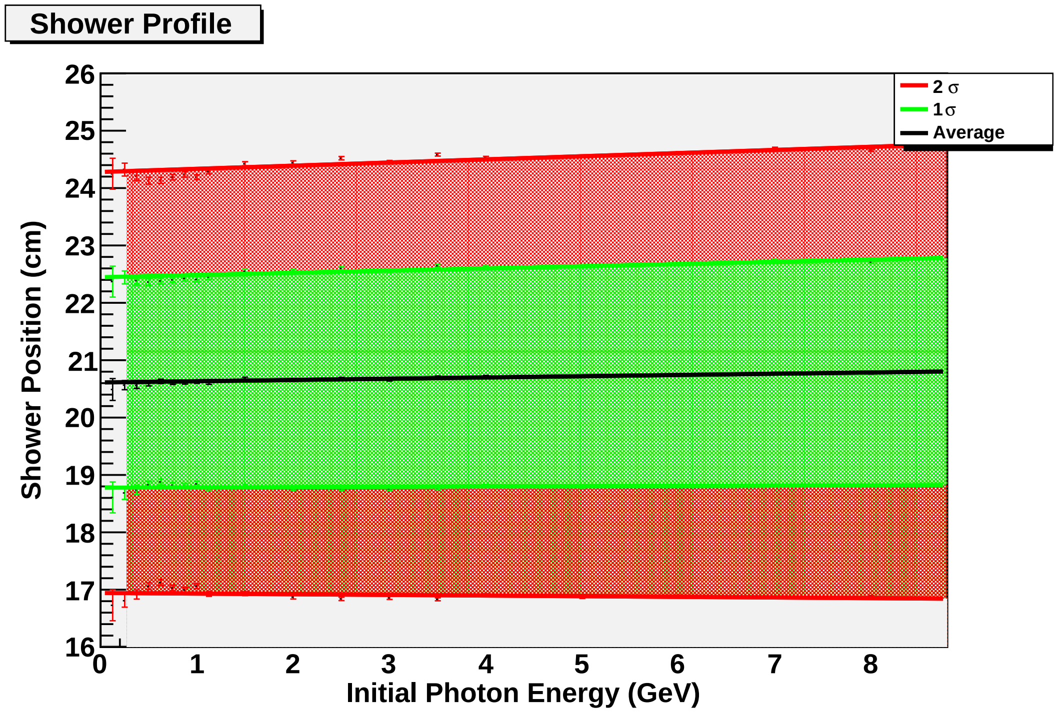

Figure 14: Average energy deposition in FCAL due to photon aimed at a radius of 20 cm on the FCAL. Green line is one sigma and red line is 2 sigma.

Another aspect to consider, is a time dependent energy resolution. If the radius is too small and some of the inner blocks become damaged the FCAL energy resolution would change over time and it would be difficult to calibrate. This means it would probably be better to take an energy resolution that was worse in the beginning by using slightly too much F108 than risk using too little and having part of the detector be undesirable by having a time dependent energy resolution. Also important, is the ability to calibrate a whole shower within the F108 entirely. If the F108 insert is too small a shower that starts in the insert will have part of it end up in the F8, this would be very difficult to calibrate. Studies were done to determine the minimum amount of F108 insert in order to get showers that are fully enclosed within the insert, see Figure 14. The figure shows that at most a shower spans 8 cm. This means it is possible for any of the proposed radii to completely enclose a shower.

7 Conclusions

Based on this analysis we propose a radius of 28 cm of F108 to be used as a radiation hard insert for the FCAL. Based on the analysis done this should be reasonably conservative in terms of damage to the blocks, the ability to reconstruct the shower, and time dependent energy resolution. This radius would require the purchase of 136 F108 lead glass blocks, see Figure 15.

A Calibrating the Linear Accelerator

The electron linear accelerator at IUCEEM was calibrated using a faraday cup, counting circuit, and GEANT4. The faraday cup was designed to directly measure the current of the linear accelerator. The

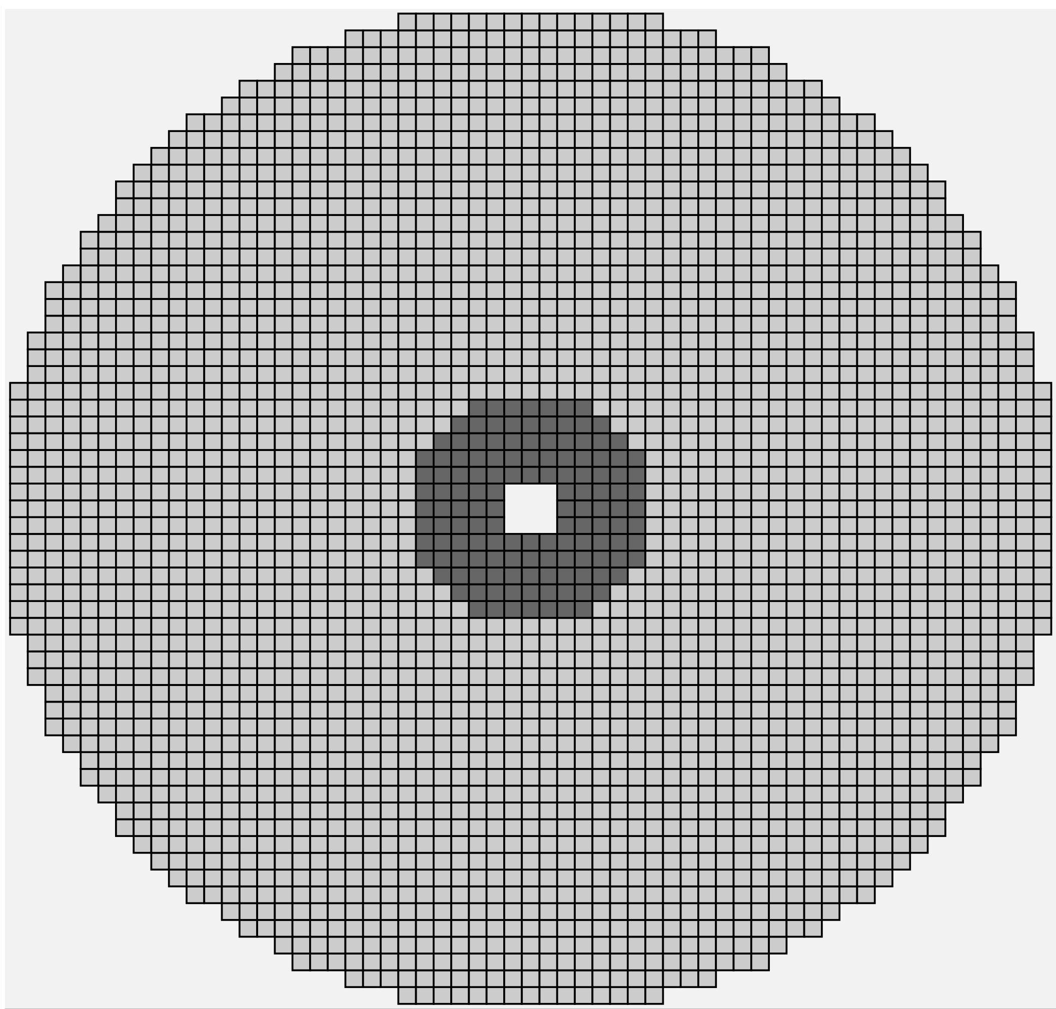

Figure 15: FCAL after insertion of 136 F108 lead glass blocks which covers a radius of 28 cm. The shaded boxes are the F108 and the non-shaded are the standard F8.

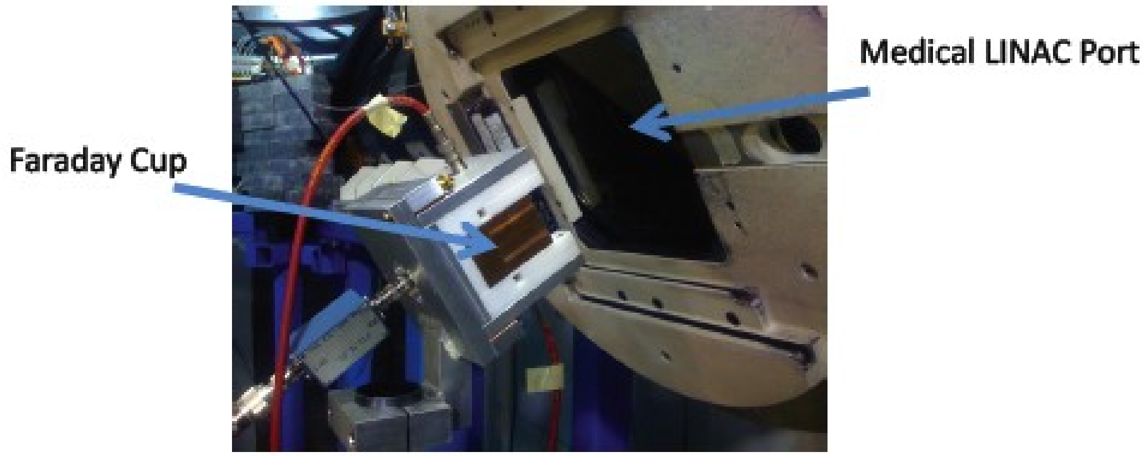

Figure 16: Photograph of the faraday cup in beam path of the linear accelerator.

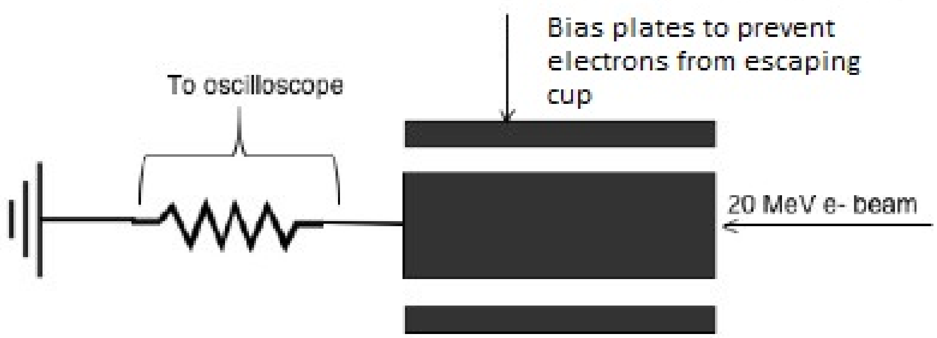

Figure 17: Diagram of the faraday cup circuit. Bias plates were set to zero voltage for the actual measurement.

cup, which is made of copper, is placed in the beam to collect the electrons, see Figure 16. In order to get a measure of the current out of the cup, a resistor was placed in the path to ground and the voltage across the resistor was measured using an oscilloscope, see Figure 17. The faraday cup is included with bias plates that were designed to stop electrons from escaping from the cup core. After many commissioning runs with many different bias voltage settings (0 - 3000 Volts), no optimum bias could be found. This was due to the fact that at a certain bias, the large potential between the plates was generating more current than the linac itself and it could not be ascertained at which voltage this process started. With no bias voltage the current was measured for an individual pulse of the machine, see Figure 18. A counting circuit was used to count the number of pulses per dose. Combining the faraday cup output and the number of counts per dose the number of electrons for each dose was determined. GEANT4 was then used to convert the number of electrons into a dosage in kRad, see Figure 6.

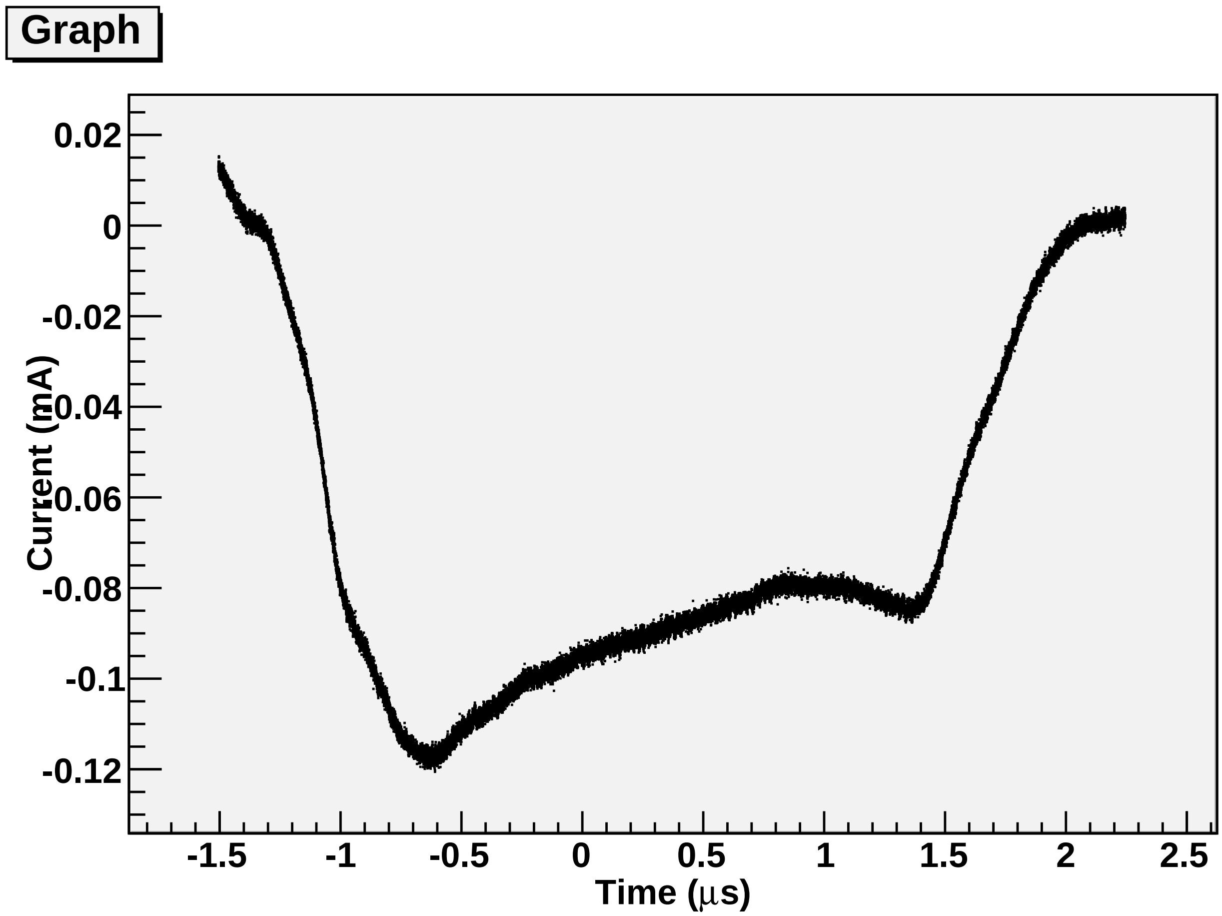

Figure 18: Graph of the current of one pulse of the linear accelerator.

B Determining the Energy Resolution and Radiation Hardness of the Radiation Hardened Glass

To properly compare a damaged regular lead glass block to a radiation hard block, the energy resolution as well as the radiation hardness of both must be known. GEANT4 was used to compare the energy resolution of F108 to F8 because it could be easily programed to include a lot of the factors that go into determining the energy resolution. These factors included PMT quantum efficiency, optical photon tracking, and index of refraction, things which are not included (by default) in HDGEANT; these factors were included in the GEANT4 simulation. The attenuation length in GEANT4 could be included as a function of wavelength and was done so using data from a spectrophotometer, Figure 4. Also included in the simulations was the quantum efficiency of the PMT, Figure 7. Simulations of the F108 (RHG) and F8 (regular lead glass) were conducted. The number of photons that hit the pmt and passed a quantum efficiency filter were counted. The number of photons detected per event is shown in Figure 19 and was fit to a modified Crystal Ball function. With this fit, the σ_n/n can be determined, which is equivalent to σ_E/E. σ_E/E vs E is shown in Figure 21 and was produced from these simulations. With this we can now compare the energy resolution ratio of RHG to F8.

The radiation hardness was tested by dosing a block of F108 with 700 kRad of dosage (this requires about 70 years of GlueX running for the inner blocks). The transmission of light through the block was measured using the spectrophotometer. Figure 22 shows spectrophotometer data for F8 and F108 both damaged and undamaged. The figure shows F108 is significantly more radiation hard than F8.

C Paper Comparison

To test the validity of the model described in Section 4, a paper by Inyakin et al. was used for comparison [3]. The paper analyzed F8 lead glass blocks damaged with 70 GeV protons. The transmission through the block was measured using four signals: green colored LED, yellow colored LED, electrons, and muons. To compare, GEANT4 was used to determine the energy deposition of the protons, Figure 23. With these simulations the transmission through the block can be calculated using the 7 mm step method in Section 5. The transmission for a single wavelength, through 45 cm of F8 lead glass, was calculated using this method. In this way the LED signal before irradiation could be compared to the LED signal after irradiation. A wavelength of 560 nm was chosen to correspond to green LED light. This process was then repeated down the block, with the value at the end compared, before irradiation and after irradiation. Figure 24 shows the comparison of the values for 560 nm to the green LED. Each point on the figure are the ratio of transmission after irradiation to the transmission before irradiation. The hollow data points are predictions based on the this damage model. The filled data points are taken from the paper by Inyakin. The paper used Equation 8.

$$e^{-N_o/b}, \tag{8}$$

where N_o is the number of protons and b is a free parameter, to fit the data points. The lines on the Figure 24 are from fits to equation 8 provided by the paper. The shaded regions are the errors on the b values.

References

[1] R.T. Jones et al. Performance of the RADPHI detector and trigger in a high rate tagged photon beam. Nuclear Instruments and Methods in Physics Research A 570 384-398. (2007)

[2] M.Kornicer. Non-linear Photon Energy Corrections in the FCAL. GlueX Note - 1093. (2008)

[3] A.V. Inyakin et al. Characteristics of Lead-glass γ-spectrometer Radiators Irradiated by High Energy Particles. Nuclear Instruments and Methods, 215 (1983) 103-106

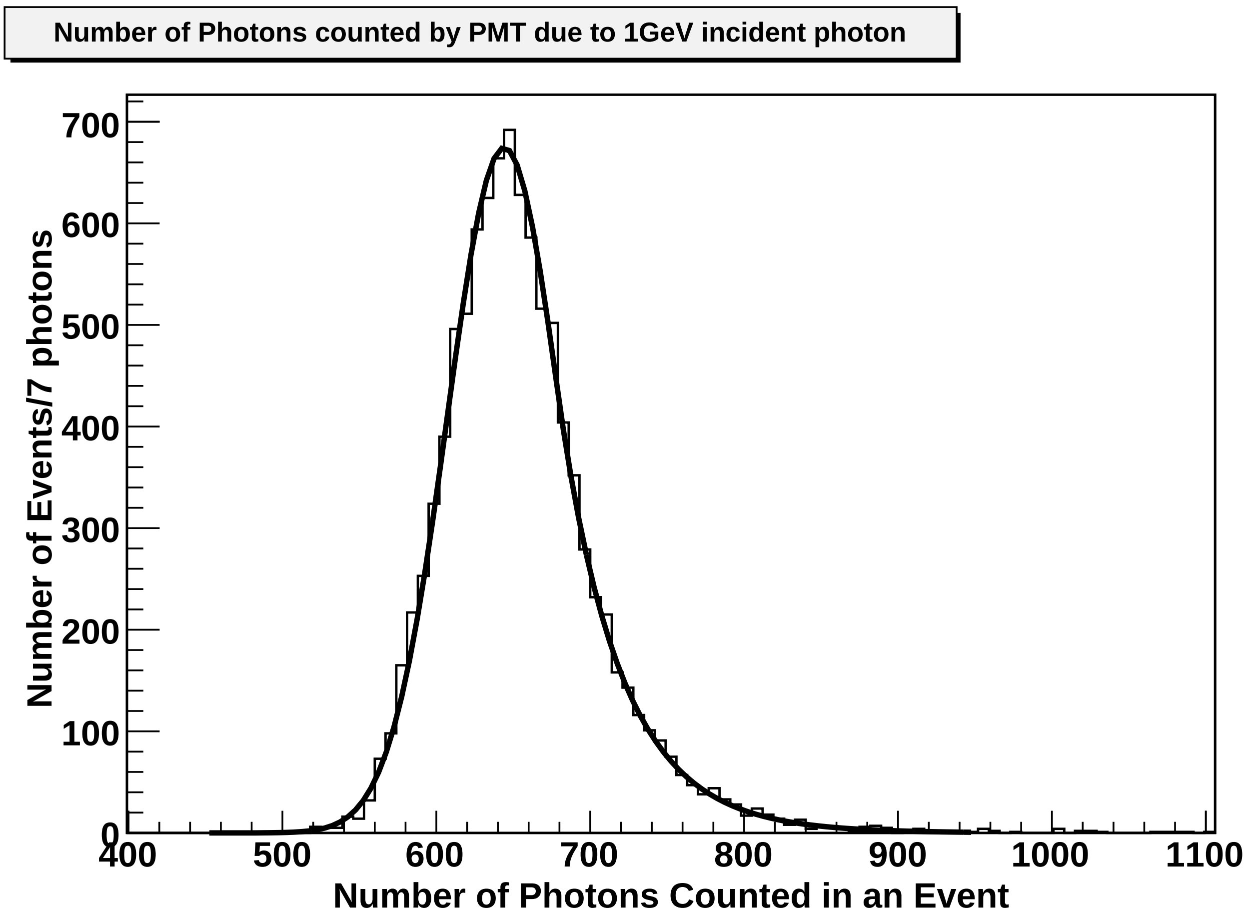

Figure 19: Number of photons detected in PMTs per event. Fit is from a modified Crystal Ball Function.

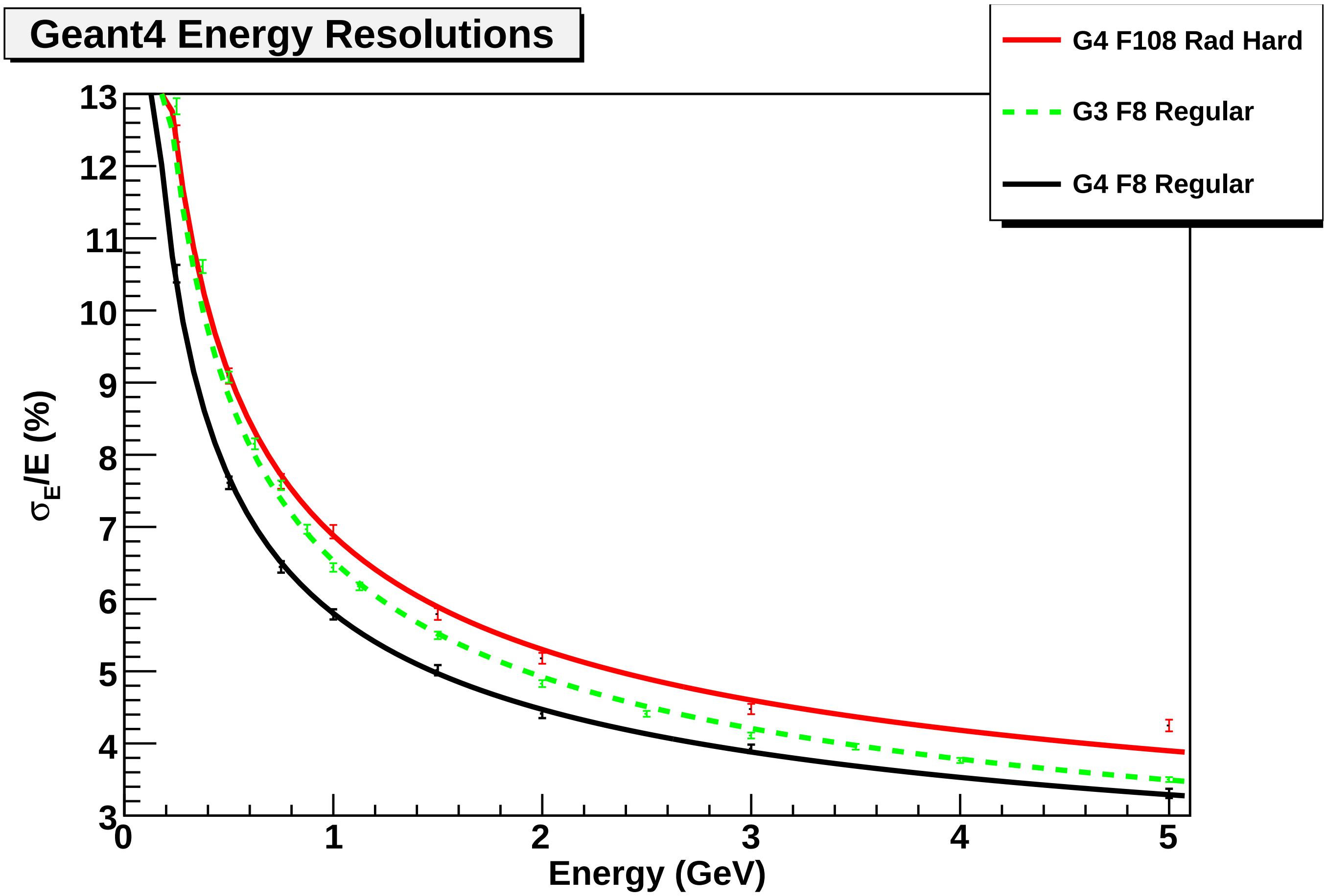

Figure 20: GEANT4 simulation of energy resolutions. The two solid curves correspond to the F108, radiation hard glass, and F8, regular lead glass. The dashed curve corresponds to HDGEANT simulation of F8.

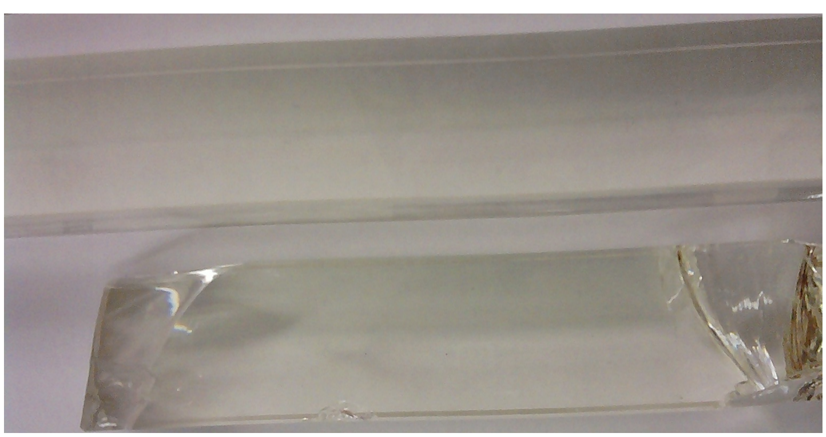

Figure 21: Photograph of F108, radiation hard glass. Top block is undamaged RHG and the bottom block is RHG dosed with about 700 kRad.

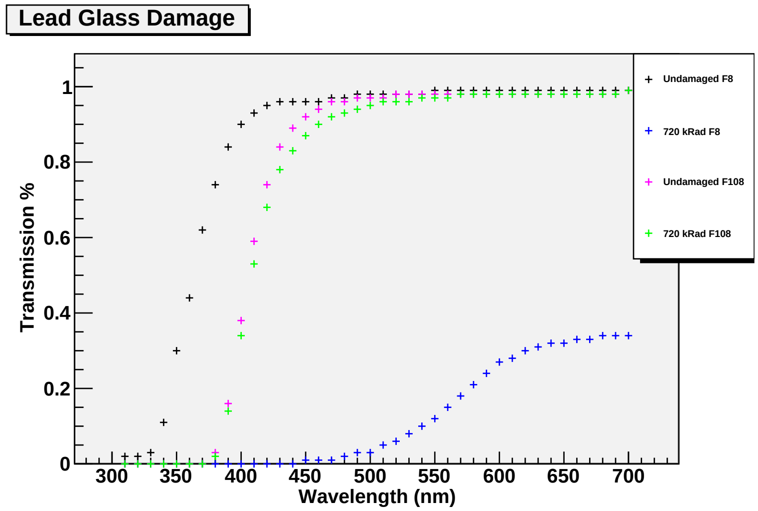

Figure 22: Spectrophotometer data of the regular lead glass, with and without damage, and the radiation hard glass. Each damaged curve is after about 720 kRad of dosage. F108 is clearly more radiation hard than F8 (green curve versus blue curve).

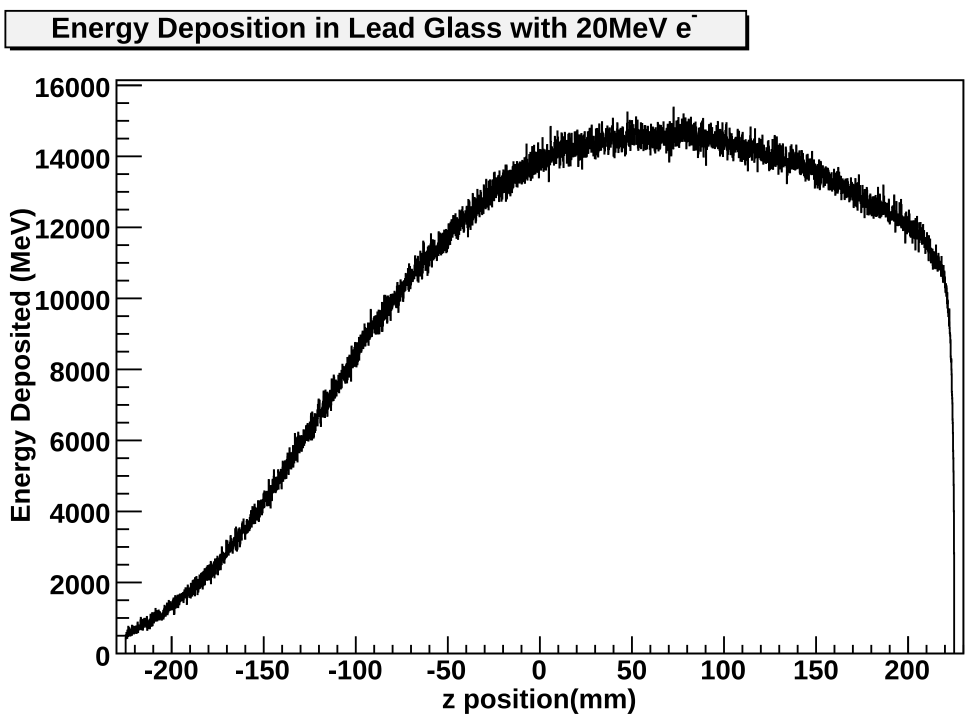

Figure 23: GEANT4 simulation of energy deposition of 70 GeV protons incident on F8 lead glass.

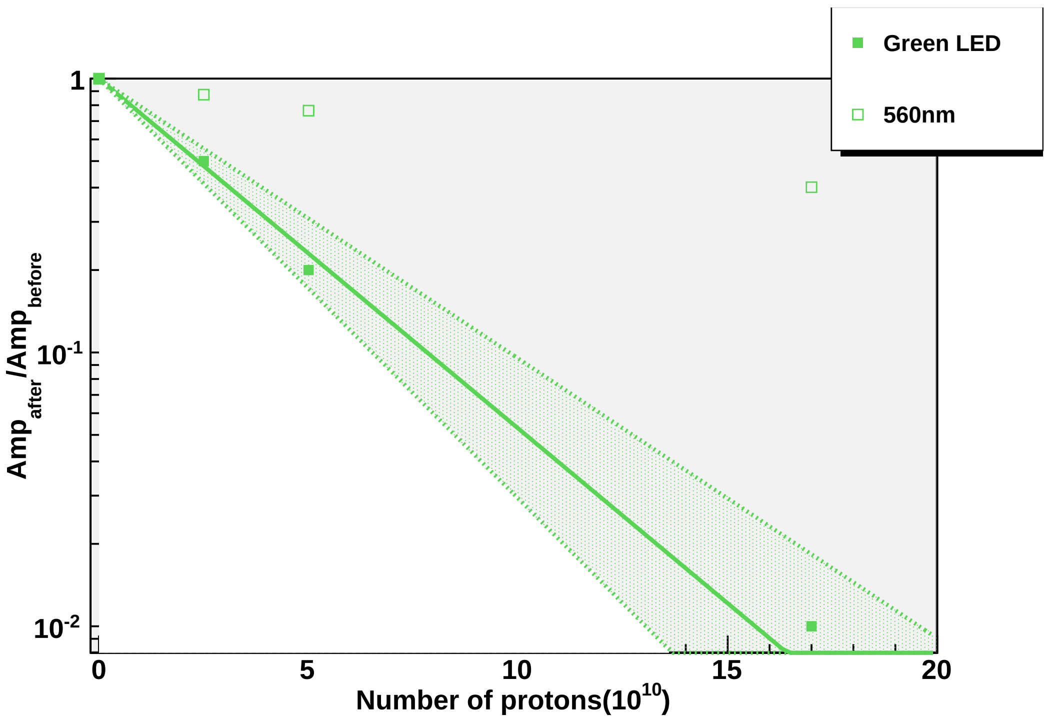

Figure 24: Results of comparison analysis. Plot shows transmission through the block after irradiation divided by transmission before irradiation. Shaded datapoints taken from reference [3]. Line is fit to data the data points with shaded area as the error. Hallow data points are predictions based on this our analysis.

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