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Scintillator Replacement Option for BaBar

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Abstract

Scintillator Replacement Option for BaBar. Michael Lometti (San Francisco State University, San Francisco, C.A., 94132) Peter Kim (Stanford Linear Accelerator Center, Menlo Park, C.A., 94025)

A replacement technology for the muon detection system in BaBar using scintillator bars with Wavelength Shifting (WLS) fibers and Avalanche Photo Diodes (APDs). APDs must be used in BaBar due to the high magnetic fields that disrupt the electron multiplying effects of Photo Multiplier Tubes (PMTs). Muons passing through scintillator cause fluors in the scintillator to emit photons, which are captured by WLS fibers and then re-emitted at the ends of the fibers to awaiting APDs. The detector configuration that will produce the largest Light Yield (LY) and produce a clear APD signal that will be larger than background noise is the main goal of the study. Bar dimensions, number of WLS fibers, and placement of fibers are parameters that may be adjusted to produce the largest LY. Additionally, good timing resolution is needed to determine where a muon passed through the detector along the long direction of the bar. A scintillator bar 2cm x 4cm in x-y with four round 1mm fibers produced the largest LY out of four different configurations with a timing resolution of 25cm. A Monte Carlo simulation confirmed the relative LY compared to other detectors. This detector was able to produce a 40mV pulse from the APD that was easily discernable above the 2-5mV background noise. Refinement of the fabrication process could produced higher LYs and better timing resolutions, while a re-design of the electronics may increase the signal to noise ratio.

Introduction

The Instrumented Flux Return (IFR) uses Resistive Plate Chambers (RPCs) as the subsystem of BaBar to identify muons. Since they were installed in 1999, the efficiency of the RPC's has been declining steadily for a mix of reasons, many of which are unknown (Ferroni, 2002).

A replacement technology for RPCs has been considered and is being explored. This technology consists of an extruded polystyrene scintillating material infused with the fluors PPO (1%) and POPOP (0.030%) and connected to a Photo-Detector (PD). A scintillation material is one that converts the kinetic energy of charged particles into detectable light (Knoll, 1989). Avalanche photodiodes (APDs) are silicon semiconductor devices, which convert optical photons to electron-hole pairs. The term "avalanche" means that, through the use of high electric fields, they incorporate internal gain in order to increase the number of charge carriers collected (Knoll, 1989) and thus increase the size of the signal collected.

At the heart of this study is the question of whether using an APD connected to a scintillator material is a viable option as a replacement. A key issue is the amount of light that is needed for the APD to register a signal above the background noise. R&D focused on what configuration of scintillator produced the highest Light Yield (LY). A Monte Carlo study was done for comparison of experiment and theory.

The R&D phase consisted of fabrication of detector prototypes and optimization of those prototypes for maximization of LY. An important concern was to avoid re-inventing the wheel by using existing technology (Schindler, 2002). Several projects including MINOS and the DØ detector at Fermilab, and CMS at CERN currently use scintillator material and PMTs in ways similar to the replacement option for BaBar. The energy spent by an ionizing particle, a muon, passing through a scintillation material goes into excitation on molecular levels and a large fraction of the excitation energy is then transformed into light, photons. (Rossi, 1952). The combination of APDs plus their readout electronics has a threshold or a minimum number of photons needed to distinguish signal from noise, so it is important to find out how many are reaching the PD. For initial testing, Photo Multiplier Tubes (PMTs) are used instead of the APDs as they have a higher gain, are (in this particular case) more durable and are on the shelf in the lab. Additionally, the PMTs have sufficient gain and low enough noise that single photons can be resolved (Caltech, 1996). Initial use of PMTs is needed to determine the signal size of a single photon, which can then be used to infer how many photons are recorded. A major problem for PMTs is that high magnetic fields in BaBar interfere with their electron multiplying capabilities. The APDs do not have this problem as they are much smaller and unwanted effects on their electric fields used to multiply the charge carriers is negligible (Knoll, 1989). A problem for affordable scintillator material is short attenuation length, that is the rate at which photons get reabsorbed by the scintillator material as a function of the length of material traversed. Additionally, the wavelength of light emitted by the scintillation material is generally not the wavelength of light that the APD is most sensitive to. These problems are overcome by the use of Wavelength Shifter (WLS) fibers epoxied into grooves milled into the scintillator. These fibers use total internal reflection to trap photons emitted by the scintillator, and having longer attenuation lengths, transmit photons to the ends of the fibers. Light produced by the passage of charged particles is multiply reflected inside the scintillator bar by an outer diffuse reflective coating and eventually is absorbed inside the WLS fiber; the fiber re-emits light isotropically and at a wavelength easily detectable by the APD. This light is then transmitted to the PDs (MINOS, 1998). Scintillator dimensions, number of WLS fibers, and placement of fibers are factors that can influence the number of photons gathered. The size of the signal received from the PMT is used to determine if a particular scintillator configuration can produce enough photons for a robust APD signal. Also of concern is the timing resolution of each scintillator: time differences can be used to determine the location at which a muon passed through the detector. Measurement of the time delay between the signal from the PMT and that of a "trigger" signal for various distances from the PMT can answer that question.

In conjunction with the R&D is Monte Carlo study. The simulation tracks a muon as it passes through a scintillator and creates photons, which are then captured by a WLS fiber. The number of photons that make it to the end of the fiber is counted. For different configurations, one can set the attenuation lengths of the scintillator and WLS fiber, the dimensions of the scintillator, and the placement and number of fibers. Running the simulation and analysis of the results provides a valuable comparison to experimental data.

The long-term goal of this project is to show that the scintillator option is a viable replacement for the RPCs in the IFR of BaBar. The short-term goal is to show that enough photons are produced to firstly, detect using an APD that a muon has passed, and secondly to determine with what accuracy the position may be known .

Materials and Methods

MINOS (Main Injector Neutrino Oscillation Search) use extruded plastic scintillator which is read out by wavelength-shifting (WLS) fibers (MINOS, 1998). This study uses the MINOS project as a jumping off point as they have similar scintillator requirements, and have studied many of the aspects of minimum cost scintillation material technology. The scintillator bars that are used in this study are the bars used in MINOS, extruded polystyrene scintillator strips, 1cm thick and 4.1cm wide with a titanium oxide outer layer for reflectivity and a groove for a 1mm WLS (Bicron BCF-92) fiber (MINOS, 1998).

The first step in the fabrication of the scintillator bar is to mill additional grooves for the WLS fibers using an end-mill attachment. A smooth rounded groove approximately 2mm deep is milled out of the scintillator. A cold gun or vortex gun, which blows cold air, is needed for all milling and cutting as the heat generated in machining melts the scintillator and makes an uneven surface. If the scintillator bars are to be sandwiched together and an optically smooth connection is desired then the bars must be planed before the grooves are cut. The planing is accomplished using a fly cutter on the milling machine and produces a smooth surface.

Surfaces that have been cut need some degree of polishing. An optically smooth surface is obtained by the use of a sanding grit less than 5μm. For surfaces that need to reflect light an aluminum oxide paint (Bicron BS-620) is used to reflect light diffusely rather than specularly.

The epoxy used to attach the fibers (Epon 815c resin and Epi-Cure 3274) is a special blend developed to be a good match with the polystyrene in terms of index of refraction (Caltech, 1998). Air-bubbles must be removed from the epoxy as they will act as small mirrors inside the scintillator and reflect the photons trying to get into the fibers. The epoxy is laid into the grooves in the scintillator and the fibers are placed in the grooves and smoothed over with the excess epoxy. The fibers must be held down with tape, as they will try to float to the surface of the epoxy while it is still liquid. A strip of aluminized Mylar is placed along the fiber to reflect any photons back into the scintillator. Approximately 15-25cm of extra fiber is left sticking out of each end to allow the attachment of the PMT/APD. The epoxy is left to harden overnight. If two bars are to be sandwiched together this is done after the epoxy holding the fibers in place has hardened using epoxy or optical grease (Bicron BC 630) to optically connect the two bars. In both cases, each bar is coated with a thick layer of epoxy/grease and sandwiched together using c-clamps to hold them together until the epoxy hardens or the tape is wrapped around them at various points ensuring a solid connection. Any excess epoxy/grease must be wiped away.

For the use of a PMT, the ends of the fibers are epoxied into a hole that has been drilled into a piece of plastic approximately 5x5cm. Once the epoxy has hardened completely the fibers are sanded down level to the surface of the plastic and polished smooth. This surface is optically connected to the PMT through the use of optical grease. For the case of the APD the fibers are epoxied into a molded plastic holder that holds the APD. Once together, the fibers are connected to the APD via optical grease.

The detector box consists of an aluminum box approximately 15x20x300cm used to protect the scintillator and the APD/PMTs from excess light. Above and below the detector on the outside of the box are smaller "trigger" detectors. The top trigger sits on a 0.5cm thick lead plate to remove low energy soft muons. The source of the muons is the upper atmosphere, where cosmic rays interacting with earth's atmosphere and produce muons. Muons readily pass through most materials so that the setup may be kept in the lab. The only downside to cosmic muons is that the flux of them through the test setup is about 800-1000 per hour for a 16cm square area and so measurements can sometimes take a while. The triggers are made with a small scintillator bar (1x4x12cm) that is optically connected to a 2cm diameter PMT using an epoxy glue. Protecting the device from outside light is accomplished by wrapping it in black electrical tape. The triggers are connected to High Voltage (HV) sources at 1885V and 1900V. The scintillator is placed inside the box and optically connected to a PMT (Phillips XP 2262B) or an APD (RMD SO223). The PMT is connected to a HV source at 1850V and a Dual Mode Discriminator (DMD). The APD is connected to a HV source at 1800V and a DMD.

The first part of the research is measurement of the amount of light reaching the PMT/APD from different positions along the scintillator bar. At predetermined positions the trigger counters are placed so that one trigger counter is parallel to the scintillator bar while the other is perpendicular to it and a 4x4cm square detection area is created. When a muon passes through the top trigger a pulse is generated from the PMT and sent to a DMD that checks to see if the signal is larger than a single threshold value. If the pulse is large enough the discriminator will produce a NIM gate, that is a -0.8V square pulse. If the incoming cosmic muon passes also through the bottom trigger counter a second NIM gate is produced. Both gates now enter a Coincidence Logical Unit (CLU) that determines if both gates are produced by the same muon by comparing the arrival times of the two gates. The gate from the top trigger has a width of 20ns, while the bottom gate has a width of 100ns. Any overlapping of NIM gates in the logic unit will produce a single 60ns wide NIM gate signaling that a muon has passed through both trigger counters. When this occurs the NIM gate from the CLU goes to an Analog to Digital Converter (ADC) and causes the ADC to integrate any charge that it receives from the scintillator during the time that the NIM gate is open. Thus a signal received from the scintillator is known to have come from a muon passing through the particular detection area defined by where the triggers are placed. The value that the ADC produces is proportional to the number of photons reaching the PMT/APD. Also being recorded is the time difference between the NIM gate from the CLU and the signal from the scintillator bar. The signal from the bar also goes to a DMD, which checks to see if the pulse is larger than two threshold values and tries to accurately determine the arrival time of the pulse (when using the ADC the accuracy of the arrival time of the pulse is not important as only the size of the pulse is being analyzed). Both gates, from the CLU and from the scintillator go to a Time to Digital Converter (TDC), with the gate from the triggers being the start time and the gate from the scintillator being the stop time. A linux PC records the TDC and ADC values and uses them to generate a distribution of the time a signal took to reach the APD/PMT from that position and of the magnitude of signal that was received from that position.

Results

Figure 1 shows the mean ADC value for each of five detector setups at 25cm from the end of the bar. Figure 2 shows a diagram of each of the five setups in the x-y plane.

Figure 3 is a plot of the mean ADC values at 25cm intervals for detector # 4 with an exponential curve fitted to the data. Figure 4 is a plot of mean ADC for several positions along the bar for detector #1.

Figure 5 is a plot of the mean TDC values for detector #4 at 25cm intervals.

Figure 6 is a spreadsheet of the results from the Monte Carlo simulations. The five setups are reproduced and values for the mean number of photons produced and photons captured in the PD and the values for the mean percentage of photons transmitted and photons captured in the photo-detector are displayed at 25 cm intervals using 1000 muon interactions. Figure 6a is a plot of the mean number of photons captured in the PD at 25cm intervals for each of the five configurations.

A photograph of the oscilloscope with the trigger gate on channel 1 and the APD signal on channel 2 is shown in figure 7. The vertical scale is 200mV for channel 1 and 20 mV for channel 2 with the horizontal scale at 500ns.

Figure 8 is a histogram of the ADC counts for Detector # 4 at a position of 25cm with a Gaussian curve fitted to the data. Figure 9 is a histogram of TDC count values for positions

25cm and 175cm with Gaussian curves fitted to both sets of data. Figure 10 is a histogram of ADC counts for the 40cm version of Detector #4 at a position of 25cm.

Discussion and Conclusion

Detector #1 is the configuration used in MINOS, and so was the first setup tested. To try to gather more light, first one and then three extra fibers were epoxied into a 1cm thick scintillator bar resulting in detectors #2 and #3. It is known that a Minimum Ionizing Particle passing through a polystyrene material will produce approximately 600 photons/cm and so a logical next step to achieve a higher LY is to increase the average path length of a muon through the material. Detector #4 is where two scintillator bars have been sandwiched together and optically connected via optical grease with a total of four WLS fiber going to the PMT and a total thickness of 2cm. The maximum space available in the IFR for a scintillator bar is 2.2cm. Detector #5 is an intermediate stage between detectors #3 and #4, it is two bars sandwiched together but not optically connected with four WLS fibers going to the PMT. Each bar has two WLS fibers epoxied into it. Figure 2 is a diagram of each of the five setups. From figure 1 it can be seen that detector #4 delivers the most photons of all setups from a distance of 25cm from the end of the bar. Data was not taken at distances less than 25cm from the end of the bars to avoid signal variations due to differing treatments of the bar ends. A curious result is the relative closeness of the mean ADC value for detectors #4 and #5. It can be seen from figure 6 and 6a that the Monte Carlo simulation suggests that the mean ADC value for detector #4 should be approximately 20% higher than that of detector #5. However, from figure 1 it is seen that it is only 2% higher. This seems to be due to the bars in detector #4 not being totally optically connected to each other. The method of planing off the layer of reflective paint and then polishing smooth the surfaces to be connected may not be the best way of creating a 2 cm x 4 cm bar with four WLS fibers in the center of the detector. More research needs to be carried out to determine the optimum method for fabrication of this configuration.

Detector #4 was then placed back into the box and ADC/TDC measurements were taken at 25cm intervals to determine the Effective Attenuation Length (EAL) and the timing resolution. The EAL may be found by looking at figure 3. A histogram of ADC counts for detector # 4 is provided in figure # 8 with a Gaussian curve fitted to the data. An exponential curve has been fitted to the data and from the reciprocal of the exponent, the EAL may be calculated. The EAL has been found to be 217cm. The advertised attenuation length (350cm) is based of the photon traveling in a straight line down the length of the WLS fiber. The EAL is due to the photon bouncing off the sides of the fiber as it propagates down the fiber and thus has a longer path length. The final size of the scintillator bars that go into BaBar will be 400 cm long; with an EAL of 215cm almost 75% of the light produced from a muon passing through the detector at one end will be lost traveling to the other end. Figure 4 is a similar graph showing that the EAL for detector #1. The value is approximately equal to detector # 4 due to the large uncertainties in fabrication. This means that the EAL should not change as new configurations are tried out in the future, as long as the same materials are used.

In figure 7 it is seen that as the triggers are moved 25cm further away from the photo-detector the mean TDC value increases by approximately 25 counts. This seems to indicate that the timing of the signals as the interaction point moves further from the PD is linear. Figure 9 shows histograms of TDC counts for 25cm and 175cm with gaussian distributions fitted to each set of data. The sigma of each gaussian can be used to find the resolution in time of the scintillator. The time value of a single TDC count has been found to be 0.069ns, this value multiplied by sigma is the resolution in time. The position resolution may be calculated by multiplying sigma by the position separation of the sets of data and then dividing by the change in mean TDC count. Thus the near position resolution is 26cm and the far position resolution is 24cm, an 8% decrease.

Figure 10 shows the histogram of ADC counts for the 40cm version of detector # 4. The amount of light reaching the PMT has been reduced through the use of an air gap and diffusing material. A single photon peak can be seen at an ADC count value of 20 with three other peaks at 10 count intervals. This indicates that the ADC count value for a single photon is 10 counts. The mean ADC count value of 680 for detector # 4 at 25cm would then translate to approximately 70 photons being collected by the PMT.

Figure 8 is a photograph of an oscilloscope showing a signal from the APD triggering off the external scintillator triggers. The detector being used is a 40cm version of detector #4. Indeed a signal approximately 40mV high, about 3-5 times larger than the background noise, can be seen in Figure 7. The large width seems to be due to the electronics and specifically from the pre-amp, and may be reduced with further refinement of the electronics.

In conclusion, it has been shown that a 2cm thick scintillator bar with four fibers results in a larger signal being read at the PD than 1cm thick with one fiber, with a position resolution of approximately 25cm throughout the bar. Additionally, the use of a shorter version of detector #4 resulted in the successful detection of a muon using the APD. An optimized version of this detector is likely to meet BaBar's needs.

Figures

Acknowledgements

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Lastly, I would like to thank Stanford Linear Accelerator Center for hosting such a wonderful experience.

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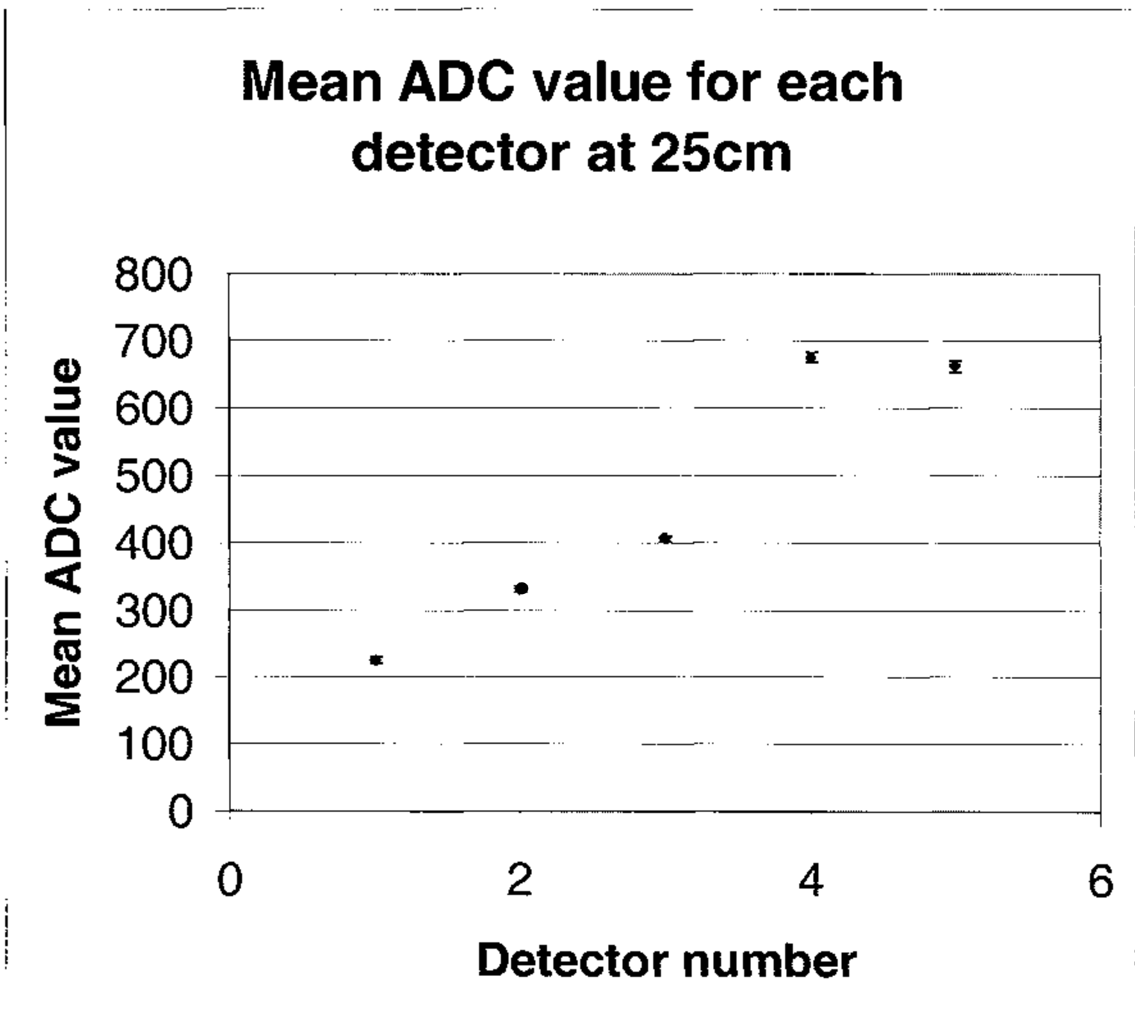
Figure # 1

	Mean ADC value at 25cm	Error
Detector #1	223.55	4.5
Detector #2	331.29	4.6
Detector #3	406.82	3.3
Detector #4	675.69	6.6
Detector #5	662.58	9.06



Mean ADC value for each of the five detectors at a distance of 25cm from the end of the scintillator.

Figure # 2

Detector #1 w/ 1 fiber at the surface.

1 cm

4 cm

Detector # 2 w/ 2 fibers at the surface.

1 cm

4 cm

Detector # 3 w/ 4 fibers at the surface.

1 cm

4 cm

Detector # 4 w/ four fibers in the center

2 cm

4 cm

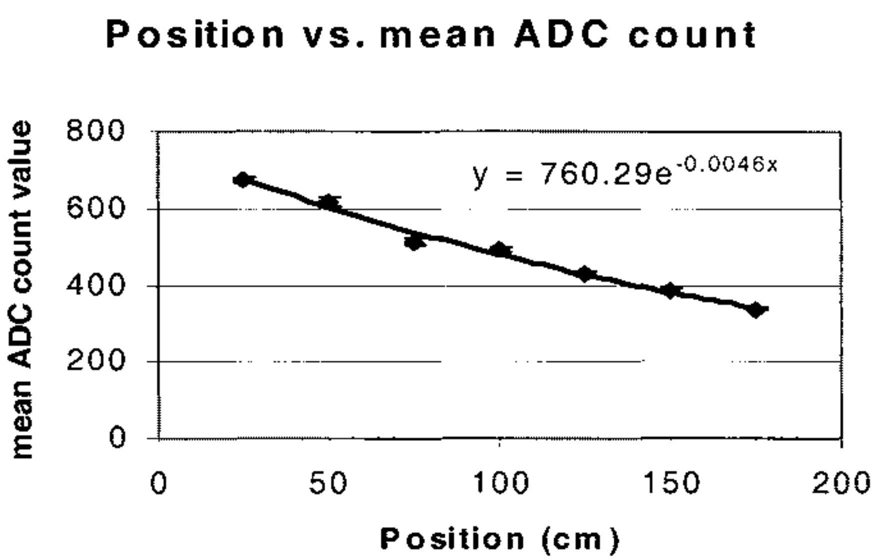
Detector # 5 w/ 4 fibers at the center.
The two scintillators are optically separtated.

2 cm

4 cm

Figure # 3

Position	Mean ADC Count	Errror
25	675.69	6.579
50	617.66	10.3
75	511.66	9.448
100	490.95	5.712
125	430.24	7.472
150	382.84	6.57
175	335.1	2.644

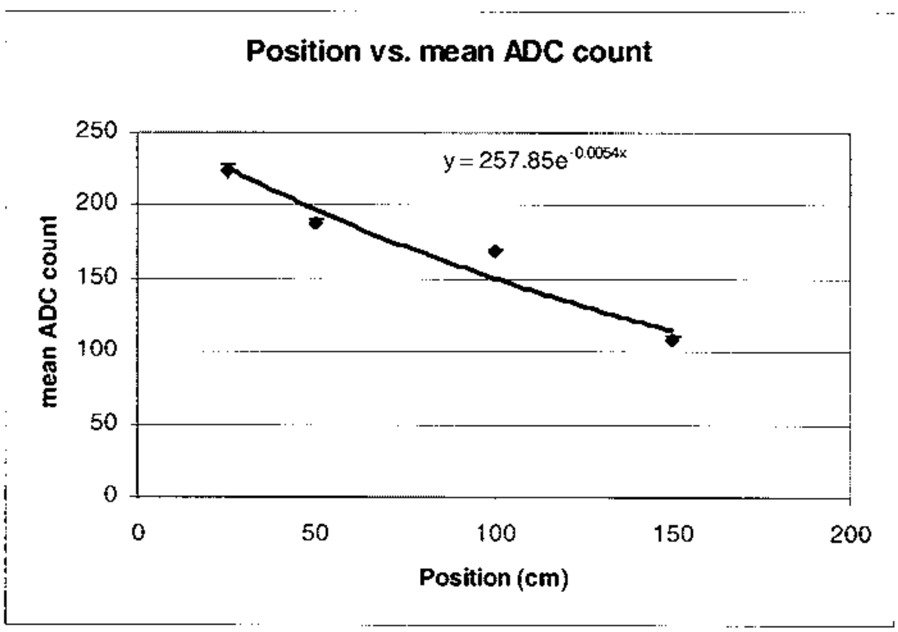


Mean ADC values for Detector #4 at 25cm intervals with an exponetial curve fitted to the data. The reciprocal of the exponent gives the Effective Attenuation Length of Detector #4.

1/.0046=217.3913

<u>**Figure # 4**</u>

Position	Mean ADC Count	Error
25	223.55	4.5
50	187.89	2.6
100	168.75	2.2
150	108.32	2.6

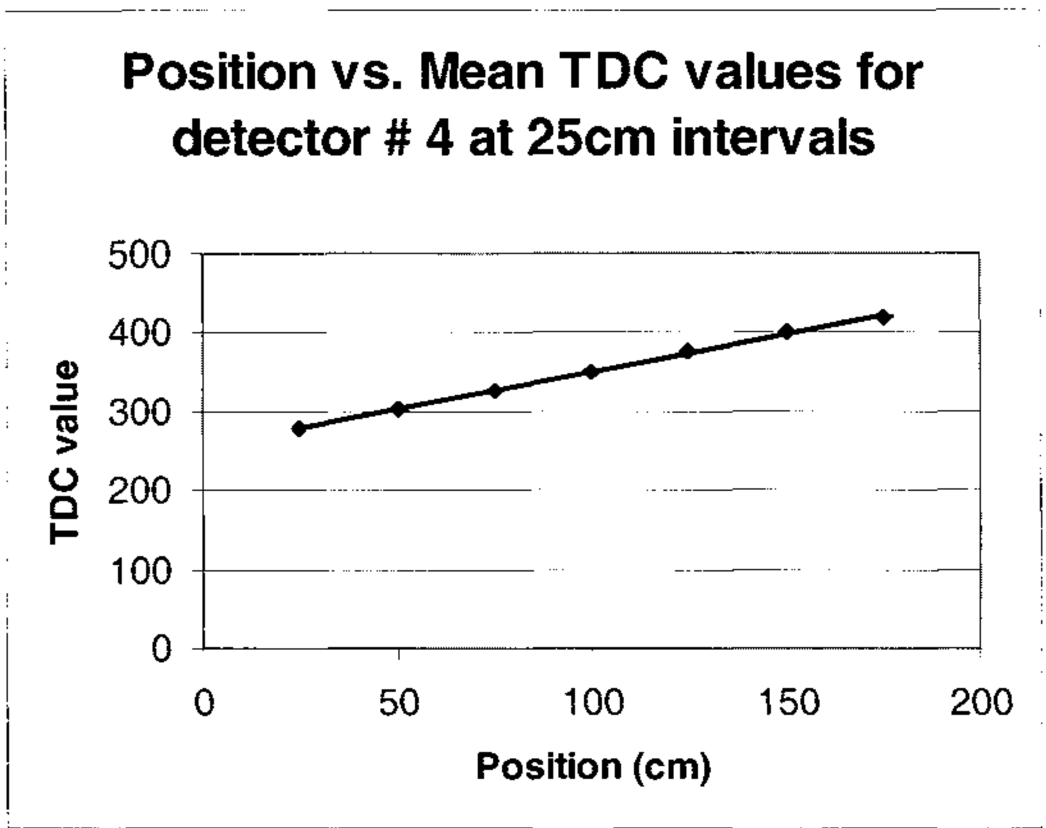


Mean ADC value for Detector #1 at 25cm intervals with an exponential curve fitted to the data. The reciprocal of the exponent gives the Effective Attenuation Length for Detector #1.

1/.0054=185.1852

Figure #5

Position	Mean TDC values	Error
25	278.65	0.87
50	301.82	1.81
75	326.08	1.74
100	351.41	1.33
125	377.01	0.91
150	399.98	1.41
175	420.55	0.88



Mean TDC count values for Detector #4 at 25cm intervals. Note that the data is nearly linear.

Figure # 6

Detector # 1 1cm x 4cm w/ 1 fiber at 90% of height (surface)

length	mean # of photons produced	mean # of photons transmitted	mean # of photons captured in PD	mean % of photons transmitted	mean % of photons captured in PD
25	609.961	8.407	6.737	1.35601	1.08491
50	608.139	7.744	6.107	1.25844	0.992154
75	609.582	7.531	5.962	1.22032	0.964094
100	614.665	7.46	5.876	1.19672	0.941312
125	611.343	7.116	5.614	1.14333	0.901962
150	607.419	6.926	5.43	1.12929	0.886353
175	606.27	6.502	5.159	1.05505	0.834136

Detector # 2 1cm x 4cm w/ 2 fibers at 90% of height (surface)

length	mean # of photons produced	mean # of photons transmitted	mean # of photons captured in PD	mean % of photons transmitted	mean % of photons captured in PD
25	613.167	14.886	11.825	2.40206	1.90651
50	610.005	13.949	11.11	2.25097	1.79715
75	606.697	13.137	10.463	2.13837	1.70429
100	607.828	12.907	10.224	2.10673	1.67163
125	606.466	12.308	9.813	2.01147	1.60386
150	606.7	12.16	9.642	1.97796	1.57016
175	613.462	11.956	9.495	1.93255	1.53636

Detector # 3 1cm x 4cm w/ 4 fibers at 90% of height (surface)

length	mean # of photons produced	mean # of photons transmitted	mean # of photons captured in PD	mean % of photons transmitted	mean % of photons captured in PD
25	598.088	21.951	17.583	3.3232	2.90191
50	607.35	21.298	17.13	3.47034	2.79187
75	607.617	20.596	16.377	3.35012	2.66878
100	598.012	19.412	15.462	3.21805	2.55724
125	609.745	19.514	15.478	3.17336	2.51361
150	606.817	18.698	14.926	3.03941	2.42831
175	608.202	17.633	14.063	2.85586	2.27979

Detector # 4 2cm x 4cm w/ 4 fibers at 50% of height (center)

length	mean # of photons produced	mean # of photons transmitted	mean # of photons captured in PD	mean % of photons transmitted	mean % of photons captured in PD
25	1176.64	36.453	29.017	3.03359	2.41375
50	1165.16	34.172	27.209	2.8809	2.28685
75	1171.67	33.025	26.331	2.76806	2.20499
100	1168.65	31.987	25.414	2.69246	2.13924
125	1184.98	31.69	25.226	2.62404	2.08577
150	1175.4	29.89	23.689	2.49881	1.98246
175	1180.7	29.275	23.277	2.43793	1.93374

Detector # 5 [1cm x 4 cm w/ 2 fibers at 90% of height (surface)]x2

length	mean # of photons produced	mean # of photons transmitted	mean # of photons captured in PD	mean % of photons transmitted	mean % of photons captured in PD
25	1226.334	29.772	23.65	2.40206	1.90651
50	1220.01	27.898	22.22	2.25097	1.79715
75	1213.394	26.274	20.926	2.13837	1.70429
100	1215.656	25.814	20.448	2.10673	1.67163
125	1212.932	24.616	19.626	2.01147	1.60386
150	1213.4	24.32	19.284	1.97796	1.57016
175	1226.924	23.912	18.99	1.93255	1.53636

<u>Figure # 6a</u>

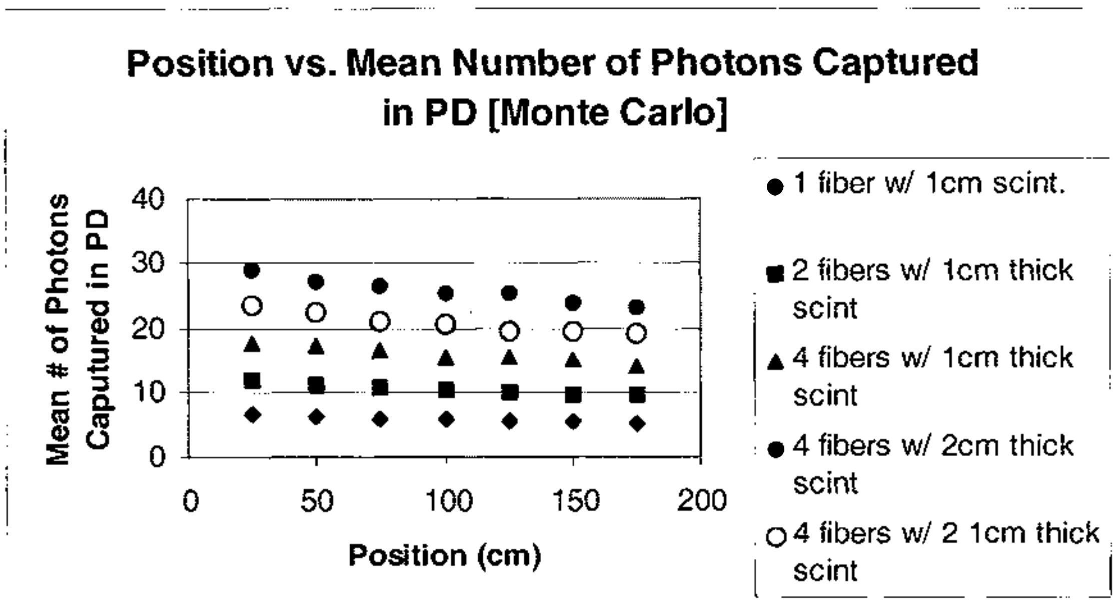
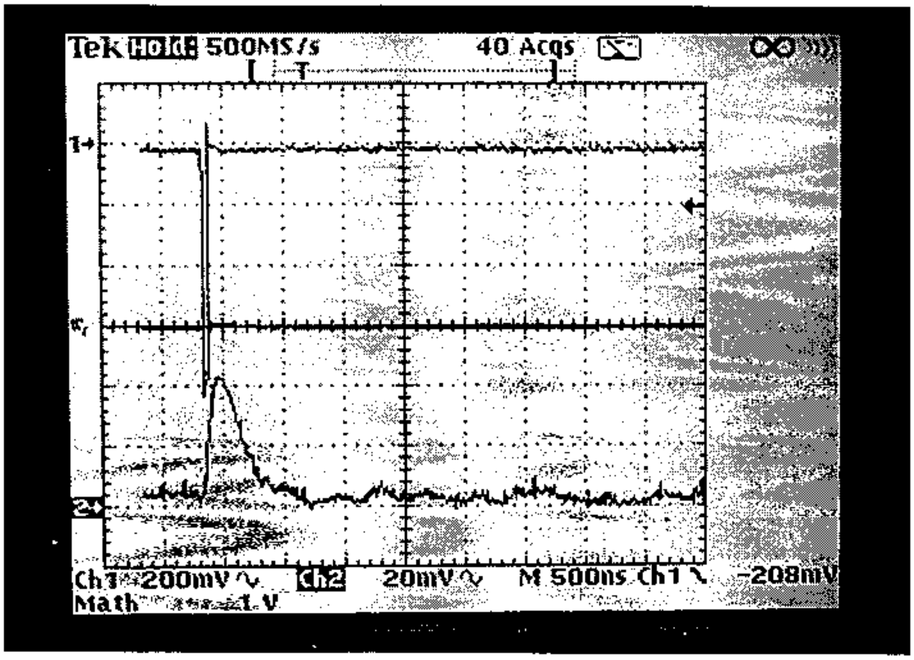
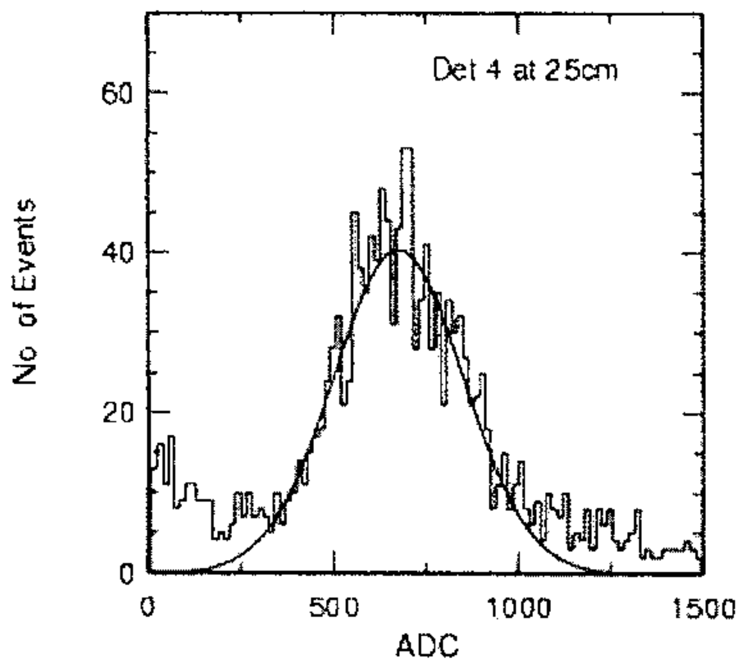


Figure # 7



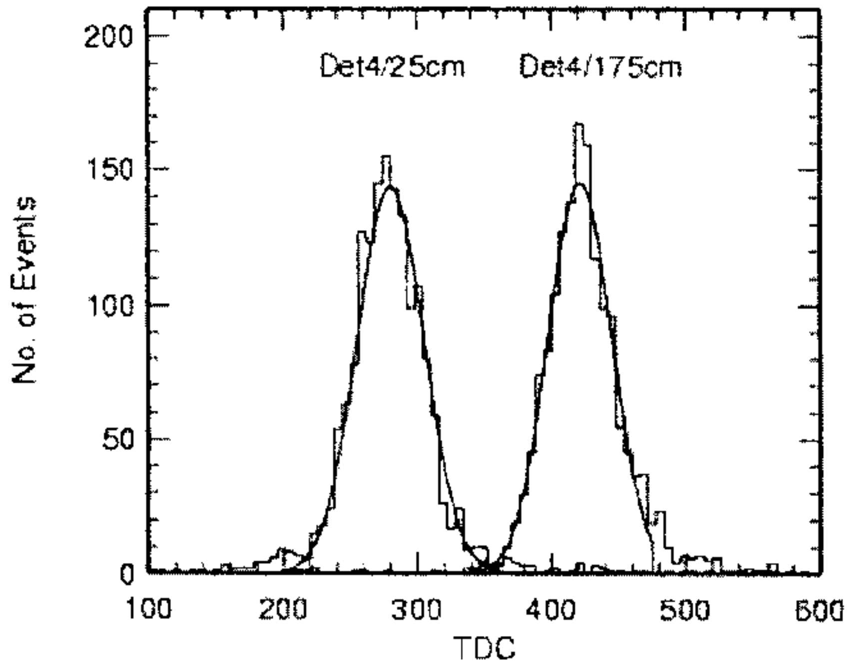
Photograph of oscilloscope showing the trigger gate on channel #1 and the signal from the APD on channel #2.

Figure #8



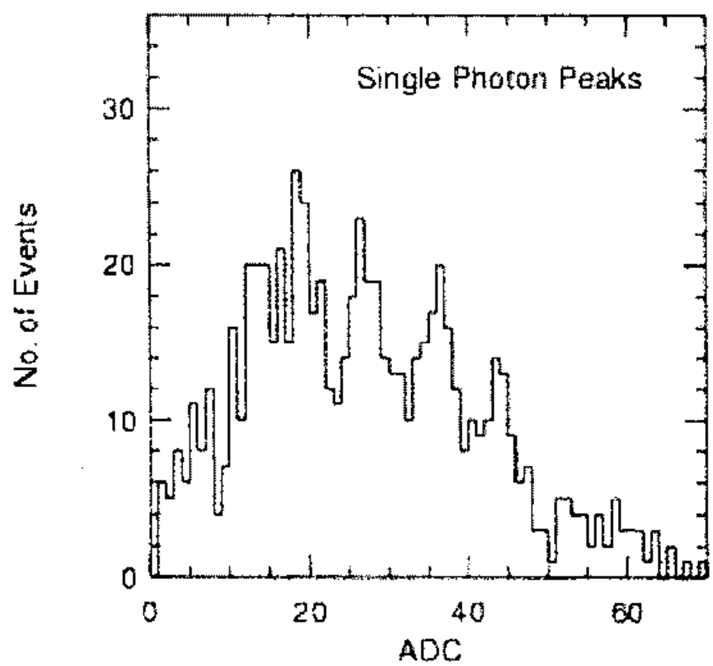
Histogram of Minimum Ionizing Particle ADC count values with a Gaussian curve fitted to the data. Note that the peak is around 700 counts.

Figure # 9



Histograms of Minimum Ionizing Particle TDC count values for Detector # 4 with Gaussian curves fitted to the data. The left histogram is for a position of 25cm and the right histogram is for a position of 175cm.

Figure # 10



Histogram of Minimum Ionizing Particle ADC count values for 40cm version of Detector # 4. Note the four distinct peaks starting at an ADC value of 20 with 10 count spacing.