

Coupling Tests for 5" Hamamatsu PMT

Thomas Fitz-Gerald

Department of Physics, University of Regina, Regina, SK, S4S 0A2

September 19, 2013

Abstract

The SHMS Heavy Gas Čerenkov detector is a part of the 12 GeV upgrade of the Thomas Jefferson National Accelerator Facility. The testing of the two optical couplings between the quartz components, namely the coupling of the quartz adapter to the PMT and of the quartz window to the adapter, are of critical importance. This report details the examination of the materials used in the two optical couplings. The results indicate that, of the materials examined, the silicon RTV works best for the coupling of the quartz adapter to the PMT and the silicon grease works best for the coupling of the quartz adapter to the quartz window.

Table of Contents

- I. Introduction
- II. Gain Testing
- III. PMT-Adapter Coupling
- IV. Adapter-Window Coupling
- V. Conclusion

1 Introduction

The Thomas Jefferson National Accelerator Facility (JLab) is continuing its 12 GeV upgrade. As part of the JLab 12 GeV upgrade, the Experimental Halls A, B and C are each being upgraded and an entirely new hall, Hall D, has been constructed. As part of the upgrade of Hall C, the Heavy Gas Čerenkov (HGC) is under construction at the University of Regina, for use in the Super High Momentum Spectrometer (SHMS). The primary purpose of the HGC is to be able to distinguish between charged kaons and pions. To meet this goal, the HGC makes use of the electromagnetic phenomenon of Čerenkov radiation; charged particles travelling through an optical medium emit light if their velocity exceeds the speed of light in that medium. To distinguish particles in the HGC, a specific gas, C_4F_8O , was selected due to its optical and other properties.

The design of the HGC makes use of four 5" Hamamatsu photomultiplier tubes (PMTs), model number R1584, for detection of the Čerenkov light that is emitted by the particles travelling through the heavy gas. Further information regarding the PMTs can be found in Ref. [1]. However, since the gas must be contained in the detector vessel and the surfaces of the PMTs are curved, two additional optical elements are necessary. The first of these is the quartz window, which allows the PMT to see into the HGC vessel but traps the heavy gas inside. The second is the quartz adapter. The quartz adapter is used to couple the curved surface of the PMT to the flat surface of the window. Each of these interfaces poses a problem due to potential loss of photons at each boundary. This is further exacerbated by the fact that each of these couplings could also have an air gap, which would further reduce the amount of light reaching the PMTs.

The problem of determining the best material to assist in the coupling of the quartz optics is the primary concern of this report. The three couplings presented in this report are: air gap, silicon grease and silicone elastomer RTV for coupling the curved PMT surface to the curved quartz adapter. The particular grease used was Eljen Technologies, EJ-550 silicone optical grease. Further information about the grease may be found in Ref. [2]. The RTV used was Momentive silicone RTV which has been shown elsewhere to have good UV-transmission characteristics as in Refs [3] and [4]. Information about the RTV can be found in Ref. [5]. Additionally, the coupling of the quartz window to the adapter was also tested

using the air gap and silicon grease. The RTV was not tested for the window coupling due to the fact that both surfaces were flat and it was believed that the use of the RTV would be unnecessary.

2 Gain Testing

Previously, the gain on each of the four Hamamatsu PMTs were determined by Ref. [6]. To confirm that the setup used in this work is operating properly, the results of Ref. [6] were rechecked. The method used to determine the gain was similar to the method used previously by Mr. Fischer. Figure 1 shows a diagram of the setup in the dark box. Full details are given in Ref. [6], they are briefly summarized here for clarity. One of the PMTs was set up in the dark box. A piece of quartz wafer was placed on top of an additional 2" PMT attached to a scintillator panel via a light guide. A β - particle source, Strontium 90, was attached to the top of the quartz wafer. Some of the β 's would then travel through the quartz generating Čerenkov radiation. The scintillator underneath the wafer acts as a trigger for data acquisition and only Čerenkov light emitted in coincidence with the scintillator would be counted in the ADC spectrum.

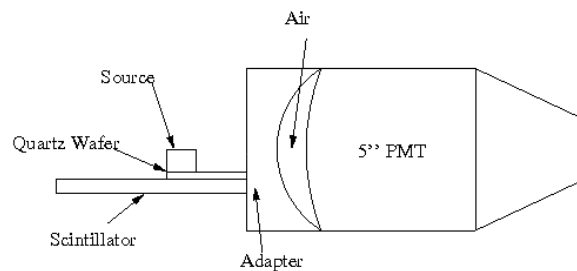


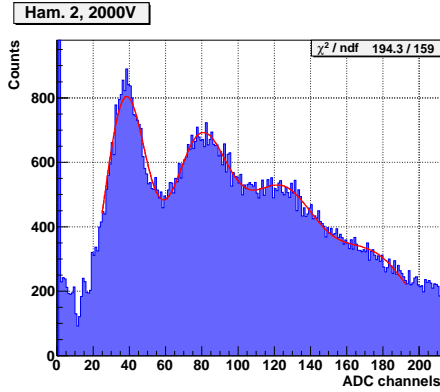
Figure 1: Diagram of the dark box setup used in the gain testing. The 2" PMT would be coming out of the page, attached to the scintillator. The difference in curvature between the PMT and the adapter is greatly exaggerated for clarity.

2.1 Gain Fit

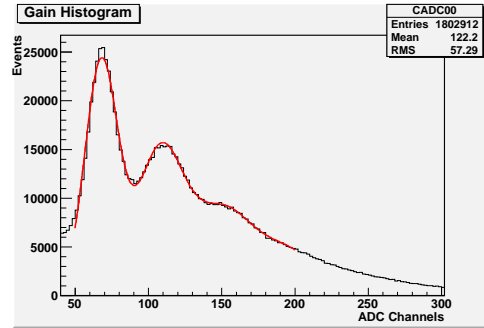
The data obtained in the gain testing was in the form of an ADC spectra. The data were fit to a sum of three Gaussian distributions, each with a centroid at one of the photoelectron peaks. Three Gaussians were chosen because only the first three photoelectron centroids were visible in the histogram. Additionally, the three centroids were constrained by sharing

| Fit | Slope | Intercept |
|-----------|-------|-----------|
| Ref. [6] | 41.7 | -4.2 |
| This Work | 40.4 | 27.4 |

Table 1: Resultant linear fit parameters from both Ref. [6] gain study and from this work. The relative difference in the slope is 3.1%.



(a) Histogram from Ref. [6].

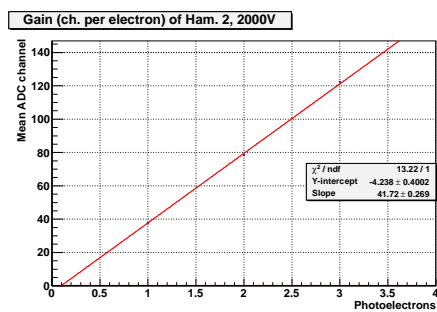


(b) Histogram from this work.

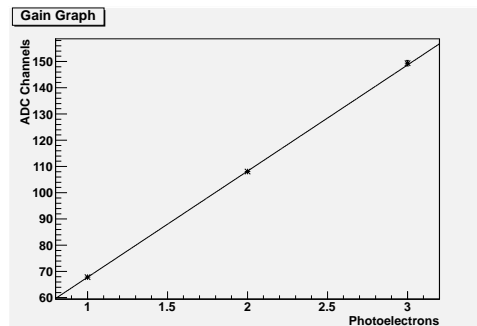
Figure 2: Gain histograms for 5" Hamamatsu PMT taken under identical conditions including the same dark box and the same voltage.

a common width. Figure 2 displays the histograms and fits obtained from the gain testing by both Ref. [6] and this work.

Once the histograms were fit with the sum of Gaussian distributions, the resultant centroids of each Gaussian were recorded. These three centroids were then used as data points in a new fit of photoelectrons versus ADC channels, of the form: $y_{ADC} = m x_{Photoelectrons} + b$ where m and b are the slope and y -intercept respectively. Figure 3 shows the results of both gain studies. The resultant fit parameters, namely the slope and intercept, are compared in Table 1. The difference in the intercepts reflects the offset of the ADC in both cases and is thus not as important as the slope of the fit. The relative difference in the slopes of both fits, defined as $(m_{PreviousWork} - m_{ThisWork}) / m_{PreviousWork}$, was found to be 3.1% which was found to be acceptable, as this was within the systematic error determined by reproducibility check in Ref. [6].



(a) Ref. [6].



(b) This work.

Figure 3: Linear fits of the peaks from the gain histograms. The resultant parameters are shown in Table 1.

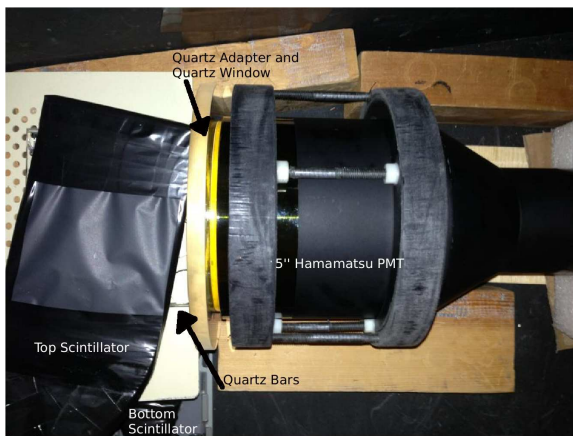
3 PMT-Adapter Coupling

3.1 Setup

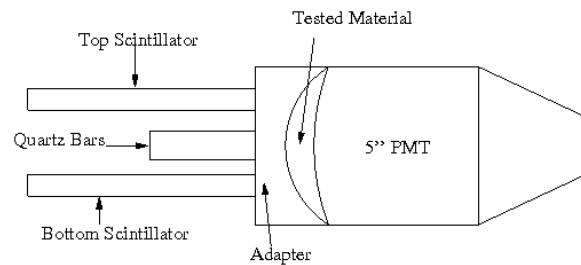
The method used to test the PMT couplings was different from that used to determine the gains of the PMTs. Figure 4 shows a diagram and a photo of the setup in the dark box. The dimensions of the quartz bars and scintillator panels used are given in Table 2. First, the PMT with the desired coupling attached to the quartz adapter was placed in the dark box. Then, two scintillators were set up one on top of the other in front of the PMT. Two quartz bars were then placed between these scintillators and touching the front of the quartz adapter. The radioactive source was removed from the box and instead cosmic rays provided the required charged particles to produce Čerenkov light. The two scintillators then acted as the trigger, only a cosmic ray passing through both scintillators would allow a signal to be read from the PMT. On the right hand side of the photograph is the PMT, held in place by the black plastic rings and pieces of wood. In the center are the quartz optical components which are in contact with the PMT on the right and the quartz bars on the left. The quartz bars themselves are not visible due to their transparency, but they sit on top of the metal shelf above and below the scintillator panels on the left. Not seen in the picture are the high voltage and signal cables running from the PMTs to the dark box wall. A schematic of the electronics used in data acquisition is explained in Appendix A.

| object | length | width |
|---------------------|---------|---------|
| Top Scintillator | 15.2 cm | 10.0 cm |
| Bottom Scintillator | 13.0 cm | 10.1 cm |
| Quartz Bars | 12.0 cm | 11.9 cm |

Table 2: Dimensions of the scintillator panels and quartz bars used in the optical couplings tests.



(a) Photograph of the dark box setup.



(b) Schematic diagram of the dark box setup for the materials tests (not to scale).

Figure 4: Diagram and photograph of the dark box setup used in the materials tests. The photograph was taken with the quartz window included, whereas the diagram only shows the quartz adapter.

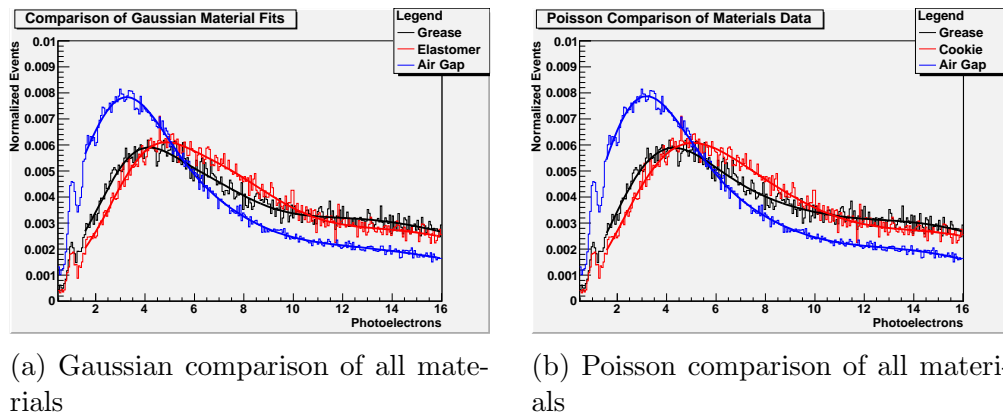
3.2 Fit Results

In order to compare the efficiencies of the three materials examined, the data obtained in the tests were fit with both a sum of three Gaussian distributions as well as a sum of three Poisson distributions, as in Equations 1 and 2 respectively. For Equation 1, there are three groups of parameters: the amplitudes (A_i 's), the means (μ_i 's) and the standard deviations (σ_i 's). For Equation 2, there are only two groups of parameters: the amplitudes (A_i 's) and the means (ν_i 's), where $\Gamma(x + 1)$ is the Gamma function. Figure 5 shows both the Poisson and the Gaussian fits of the three data sets. A sample ROOT script is given in Appendix B. Firstly, the results of the gain test were used to determine the centroid of the first photoelectron peak in the ADC spectrum by substituting $x_{Photoelectron} = 1$ into the gain formula. The resultant y_{ADC} value was then used to scale the data from ADC channels to photoelectrons by placing the location of the first photoelectron peak at one on the histogram. Then, the sum of counts in the histograms were normalized to unity in the region between the under and overflow bins. The particular fit function was then fit to the normalized data and the x -value (photoelectrons) of the maximum y -value (peak counts) in the fit was recovered. Additionally, the fits were extrapolated past the overflow bins. This extrapolation was done because of the large number of overflow counts in the ADC due to the lack of attenuation. The extrapolation was then used to determine the average photoelectrons from the fits. These two quantities: average photoelectrons and peak photoelectrons were then compared for both fit functions.

$$f(x) = A_1 e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} + A_2 e^{-\frac{(x-\mu_2)^2}{2\sigma_2^2}} + A_3 e^{-\frac{(x-\mu_3)^2}{2\sigma_3^2}} \quad (1)$$

$$f(x) = A_1 \frac{e^{-\nu_1} \nu_1^x}{\Gamma(x+1)} + A_2 \frac{e^{-\nu_2} \nu_2^x}{\Gamma(x+1)} + A_3 \frac{e^{-\nu_3} \nu_3^x}{\Gamma(x+1)} \quad (2)$$

The resulting peak photoelectrons and average photoelectrons as well as the χ^2/NDF for each fit are shown in Table 3. For comparison, the ratios of peak PE for each pair of materials were computed. These ratios are defined as $Peak_1/Peak_2$. For instance, the ratios of peak PE for the grease compared to the air gap would be $Peak_G/Peak_A = 1.28$ for the Gaussian fit (1.34 for the Poisson Fit). Table 4 shows the ratios for both peak and average PE between the three materials. From Table 4, the grease is a considerable improvement



(a) Gaussian comparison of all materials

(b) Poisson comparison of all materials

Figure 5: Comparison of the data from the PMT-adapter tests from cosmic ray data in Quartz bars. The elastomer and grease consistently outperform the air gap, but the elastomer's improvement over the grease is small.

over the air gap, while the elastomer is a smaller improvement over the grease. Also, the reduced χ^2 of the fits are all comparable and the fits appear to be equally good to the eye. The results were as expected by work done for the SHMS Calorimeter [7], with the difference between the air and grease being large compared to the difference between the grease and the elastomer. However, the elastomer also has the benefit of forming to the curvatures of both the PMT and adapter surfaces. Since these curvatures are slightly unequal, the elastomer provides an option to couple the curvatures of both surfaces. While the grease offers comparable average and peak photoelectrons, the elastomer is better at coupling the two surfaces of different curvature than the grease, due to the grease's ability to flow. Since the grease is able to flow, air could enter into any region which the grease has left due to it having flowed out. The elastomer does not have this problem, since the elastomer solidifies in the region and thus cannot flow. Care must be taken when producing the elastomer so that air is not trapped in it in the form of bubbles or is allowed to remain between the adapter and the PMT surfaces. This was done by pumping the RTV in a vacuum chamber for 30-45 minutes after mixing.

One final test was to take the fit data, extrapolate the fit after the overflow channels and then compare the integral of the fit after the overflow to the number of counts in the overflow. The results of this test showed a large discrepancy between the two integrals. This discrepancy has been ascribed to there being multiple sources of light which acted to produce

| Material | Gaussian Fit | | | Poisson Fit | | |
|----------|--------------|--------------|--------------|-------------|--------------|--------------|
| | Peak P.E. | Average P.E. | χ^2/NDF | Peak P.E. | Average P.E. | χ^2/NDF |
| Air | 3.25 | 8.01 | 1.27 | 3.19 | 7.39 | 1.27 |
| Grease | 4.17 | 10.19 | 1.20 | 4.29 | 9.55 | 1.17 |
| RTV | 4.85 | 9.89 | 0.99 | 5.07 | 9.69 | 0.99 |

Table 3: Results from the PMT coupling tests. The difference between the air gap and the grease is large compared to the difference between the grease and the elastomer.

| Ratio | Fit Functions | |
|-------------------------|---------------|---------|
| | Gaussian | Poisson |
| $\frac{Peak_G}{Peak_A}$ | 1.28 | 1.31 |
| $\frac{Peak_E}{Peak_G}$ | 1.16 | 1.18 |
| $\frac{Avg_G}{Avg_A}$ | 1.27 | 1.29 |
| $\frac{Avg_E}{Avg_G}$ | 0.97 | 1.01 |

Table 4: Ratios of peak and average photoelectrons. A, G and E stand for Air Gap, Grease and RTV respectively.

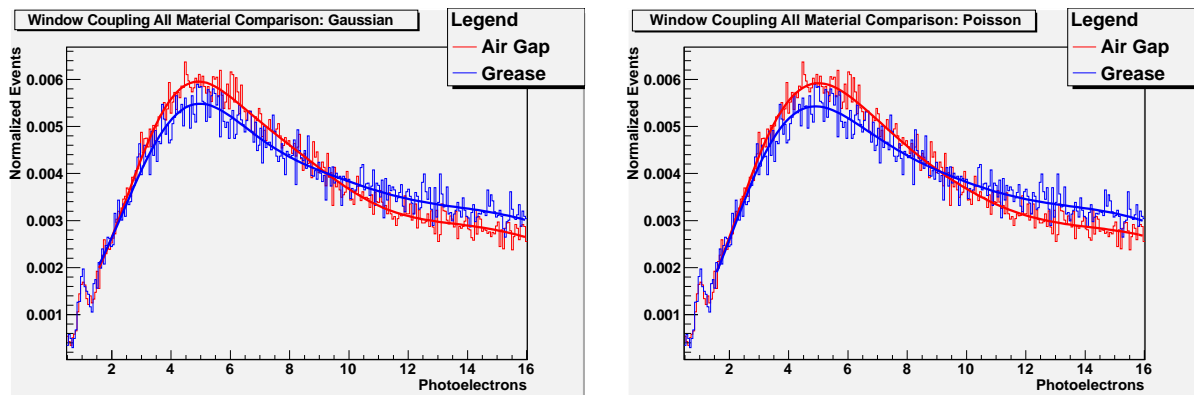
noise in the histogram. The resolution of this issue would have been to retake the data with an attenuator in the electronics scheme, thereby reducing the level of overflow. This test, however, was devised after all of the data had been taken, so time would not allow for the retaking of all of the data. Table 5 shows the number of counts in the overflow bins and the integral of the fit after the overflow for each of the fit functions.

4 Adapter-Window Coupling

Following the PMT coupling tests, further testing was required to determine the best method of coupling the quartz window to the quartz adapter. Since both surfaces were flat, the use

| Material | Overflow Counts | Gaussian Fit Integral | Poisson Fit Integral |
|----------|-----------------|-----------------------|----------------------|
| Air | 41565 | 1682 | 1001 |
| Grease | 25624 | 948 | 673 |
| RTV | 38072 | 685 | 609 |

Table 5: The results of the overflow comparison. The large discrepancy between the number of counts in the overflow channels and the integral of the function after the overflow is ascribed to there being multiple sources of light in the PMT-Quartz-Scintillator system.



(a) Gaussian comparison of window-adapter data

(b) Poisson comparison of window-adapter data

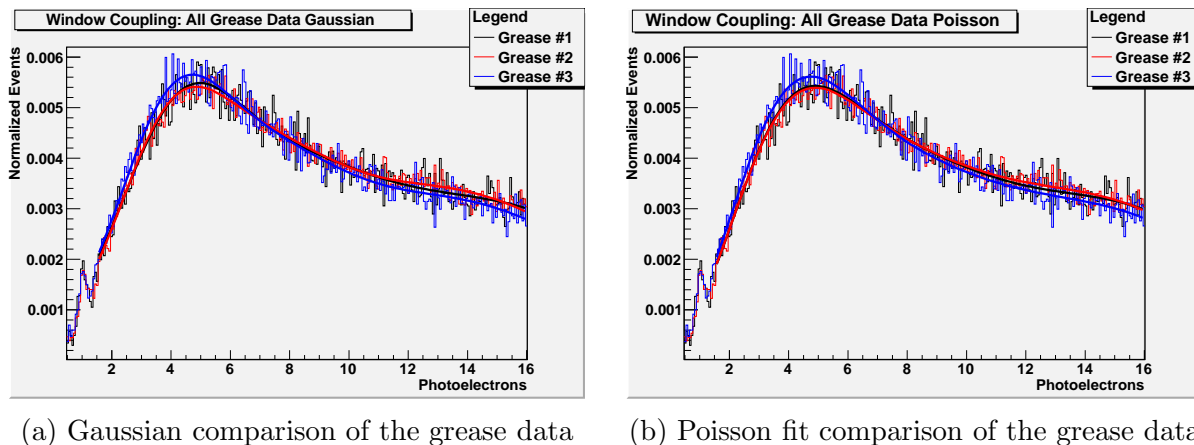
Figure 6: Comparisons of the window-adapter data.

| Material | Gaussian Fit | | | Poisson Fit | | |
|----------|--------------|--------------|--------------|-------------|--------------|--------------|
| | Peak P.E. | Average P.E. | χ^2/NDF | Peak P.E. | Average P.E. | χ^2/NDF |
| Air | 4.92 | 10.15 | 1.09 | 5.00 | 10.04 | 1.06 |
| Grease | 4.97 | 10.69 | 1.06 | 4.90 | 10.34 | 1.04 |

Table 6: Results from the Window-Adapter coupling tests.

of the RTV was considered unnecessary following the results of the PMT coupling tests. This was because the improvement of the RTV with the curved adapter over the grease was less than the improvement of the grease over the air gap. The setup of the tests was identical to the setup of the PMT coupling tests with the inclusion of the quartz window. The quartz adapter had previously been attached to the PMT with the RTV, so the tests of the window couplings would be compared to the results for the RTV. The coupling methods examined were the silicone grease and the air gap. Similarly to the previous testing, the results were fitted to both a sum of Gaussian distributions and a sum of Poisson distributions with the peak and average photoelectrons being extracted from the fits.

The expected result was that the grease would show an improvement in both peak and average photoelectrons. The Gaussian and Poisson fits showing the comparison of the air and grease are shown in Figure 6. The results of both fits are shown in Table 6. As expected, the grease showed an improvement in both peak and average photoelectrons over the air gap.



(a) Gaussian comparison of the grease data

(b) Poisson fit comparison of the grease data

Figure 7: Comparison between the three grease trials. The amount of grease used in each trial were: Grease #1: 3cm squeeze; Grease #2: 1.5cm squeeze; Grease #3: 1cm squeeze.

4.1 Grease Testing

The grease was observed to have a tendency to flow from the coupling region onto the magnetic shield of the PMT. This was believed to result in electric discharge signals from the PMT as well as leaving a mess inside the magnetic shielding, both undesirable features. Because of this fact, the amount of grease used in the coupling region would have to be reduced to the point where this flow is small but kept large enough to provide the optical benefits of the grease. Thus, two more tests of the grease coupling were devised where the amount of grease used in the coupling region was decreased until the amount of grease that had leaked out had reached acceptable levels. The amount of grease used was recorded and then the three grease data sets were fit as before and compared. Figure 7 shows both of the Poisson and Gaussian fits of the grease data while Table 7 shows the results of these fits.

The small differences between the average and peak photoelectrons indicate that more grease provides a better coupling than less grease. However, the benefits of using less grease, namely the reduction in electric discharges and the increased cleanliness of the PMT are definitely important factors along with the photoelectron figures. To this end, minimal grease was chosen as the coupling method, primarily because of the increase in cleanliness of the magnetic shield and the apparent elimination of the electric discharges from the PMT signal.

| Material | Gaussian | | | Poisson | | |
|-----------|-----------|--------------|--------------|-----------|--------------|--------------|
| | Peak P.E. | Average P.E. | χ^2/NDF | Peak P.E. | Average P.E. | χ^2/NDF |
| Grease #1 | 4.97 | 10.69 | 1.06 | 4.90 | 10.34 | 1.04 |
| Grease #2 | 4.85 | 10.33 | 1.10 | 4.90 | 10.20 | 1.01 |
| Grease #3 | 4.72 | 10.11 | 0.94 | 4.76 | 10.01 | 0.91 |

Table 7: Results from the Grease fits only. See Figure 7 for amounts of grease used in each trial. The differences between each grease fit are small compared to the differences between the grease fits and the non-grease fits.

5 Conclusion

The 12 GeV upgrade of the Thomas Jefferson National Accelerator Facility is a large undertaking requiring the upgrade of also the detectors used in the different experimental halls. The upgrade of Hall C will see the construction of the Super High Momentum Spectrometer, a component of the SHMS instrumentation is the Heavy Gas Čerenkov detector. The HGC uses four photomultiplier tubes to examine the Čerenkov light emitted by charged particles travelling through the detector. The PMTs look into the detector through two pieces of quartz optics each: the curved quartz adapter connects the front surface of the PMT and has the unique challenge of having to couple to uneven curvatures. The second optical component is the flat quartz window which allows the PMT to look into the detector vessel. The coupling of the window to the adapter is simpler than the coupling of the PMT to the adapter due to the curvature problem previously mentioned.

The coupling of the adapter to the PMT provided the challenge of coupling two surfaces of unequal curvature. The particular materials used in the coupling test were as follows: an air gap was left between the adapter and the PMT, grease was used to couple the surfaces and finally a particular silicone elastomer was used. In terms of peak and average photoelectron output, the grease and the elastomer were far better than the air gap, but the difference between the grease and elastomer was much smaller than the difference between the grease and the air gap. The elastomer, however, provided the unique ability to conform to the curvatures of both the PMT and adapter surfaces. This property of providing a form-fitting coupling, along with the small superiority of the elastomer over the grease in terms of efficiency led to the decision to use the elastomer as the final PMT-adapter coupling material.

For the window-adapter coupling, the unique coupling property of the elastomer would

not be as much of an advantage due to both the window and the adapter being flat surfaces. Further studies were then made to compare the efficiency of the silicone grease to that of having only an air gap between the window and the adapter. In terms of the peak and average photoelectrons, the grease showed an improvement over the air gap, but not as large an improvement as in the curved surface study. Thus, grease was chosen to couple the window to the adapter because of the improvement in efficiency over the air gap. The use of too much grease in the coupling region, however, was undesirable due to the grease leaking into the space between the PMT and the PMT's magnetic shielding. Thus, further studies were pursued using less grease in the region of interest. The changes in the peak and average photoelectrons were small between the three grease data sets. This coupled with the potential for problems should grease flow into the region between the PMT and the magnetic shield led to the conclusion that minimal grease in the coupling region is the most desirable. Thus, minimal grease in the window-adapter coupling was chosen as to be the final coupling material.

6 Acknowledgments

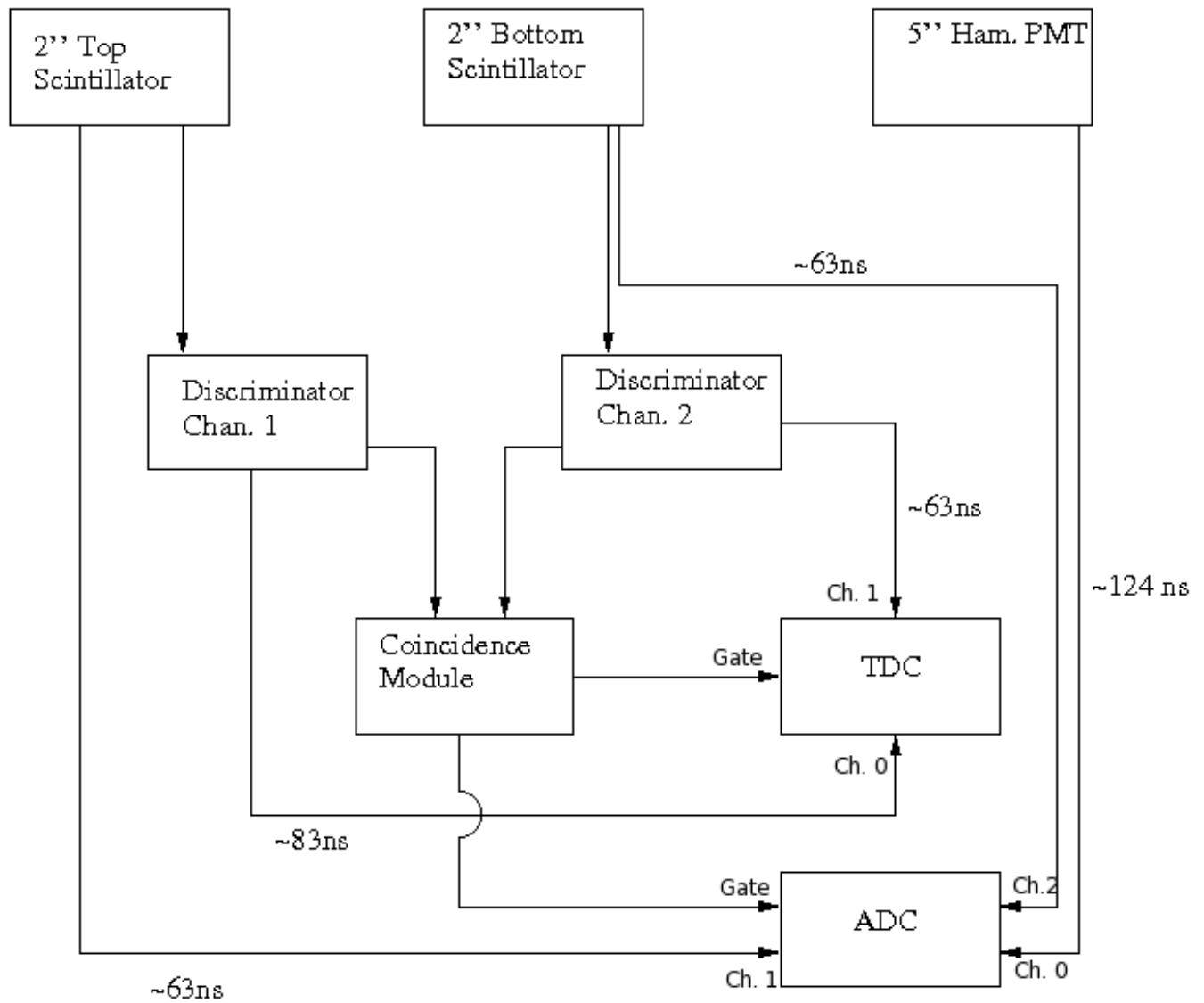
I would like to thank the Natural Science and Engineering Research Council of Canada (NSERC) for funding this undergraduate research. I would like to thank Dr. Garth Huber for the opportunity to work on this project as well as the assistance he provided in editing this report among many other things. Finally, I would like to thank Mr. Wenliang Li for the assistance he provided in the setup of the experiments, the data acquisition, as well as the help he provided me with ROOT and Linux computers in general.

References

- [1] HAMAMATSU Photonics K.K. [IR] 325-6, Sunayama-cho, Na ka-ku, Hamamatsu City, Shizuoka Pref., 430-8587, Japan. Website: www.Hamamatsu.com.
- [2] Eljen Technologies, 1300 W. Broadway, Sweetwater, Texas, 79556. Website: <http://www.eljentechnology.com>
- [3] W. Klamra, Th. Lindblad, M. Moszynski, L.O. Norlin, “Properties of Optical Greases for BaF₂ Scintillators”, Nuclear Instruments and Methods in Physics Research, Vol A254 (1987) pp. 85-87.
- [4] Laurence Reekie, Lu Chao, Morten Ibsen, “Fibre gratings written through the coating at 244nm and 248nm”, IEEE Colloquium on Optical Fibre Gratings (Ref. No. 1999/023), pp. 2/1-2/4.
- [5] Momenitive, 180 East Broad Street, Columbus, OH, 43215. Website: www.momentive.com/home.aspx
- [6] A. Fischer. “Performance Testing of 5 inch PMTs”. Hall C Document Number: HallC-Doc-738-V1.
- [7] A. Mkrtchyan, et al. “SHMS Calorimeter Status Update”, Talk Presented at the Hall C Workshop, January 13th, 2012. Slide Five.

A Electronics Schematic

Figure 8 is a schematic diagram of the electronics used in the data acquisition.



Discriminator Settings:

2'' Top: Width = 100ns

Threshold = 0.55V

2'' Bottom: Width = 100ns

Threshold = 0.48V

Coincidence Width = 100ns

All Delay amounts indicated

Figure 8: Data acquisition electronics diagram.

B Sample Script

The following is a sample C++ script for the data analysis framework Root.

```
// *****
// This script was modified by Thomas Fitz-Gerald in June 2013
// from an original made by Alex Fischer. This script fits a
// Poisson distribution to a histogram by using the
// TMath::Poisson function. Also, a function found on the
// Root website which scales the X axis of a histogram was used and
// a link is provided detailing where the function was taken from.
// *****

int PMTCouplingTestComparison3(){

    TCanvas *c1 = new TCanvas("c1"); // Create new canvas namd c1

    TFile* file_in1 = new TFile("run02047.root");
    //Read from the file "run02047.root"

    TFolder* folder1=(TFolder *)file_in1 ->Get("histos");
    //Opens the histogram folder in the file previously opened

    TH1D* photon1=(TH1D*)folder1 ->FindObject("ADC calibration/CADC00");
    // Finds the specific histogram to be fit names it photon1

    TFile* file_in2 = new TFile("run02048.root");
    TFolder* folder2 = (TFolder *) file_in2 ->Get("histos");
    TH1D* photon2=(TH1D*)folder2 ->FindObject("ADC calibration/CADC00");

    TFile* file_in3 = new TFile("run02045.root");
    TFolder* folder3 = (TFolder *) file_in3 ->Get("histos");
    TH1D* photon3=(TH1D*)folder3 ->FindObject("ADC calibration/CADC00");
    // Repeat the procedure of opening runs
    // and taking the relavent histograms

    c1->cd(); //Changes the current canvas to c1

    photon1->SetStats(kFALSE);
    /* Removes the statistics box from the canvas.
    This was done because there are multiple histograms
    plotted on the same canvas and keeping the stats box
    would have been confusing.
    */
}
```

```

ScaleXaxis(photon1, ScaleX);
ScaleXaxis(photon2, ScaleX);
ScaleXaxis(photon3, ScaleX);
/* Call to ScaleXaxis, function taken from the Root website.
Function scales the x axis of each histogram such that the
first photoelectron peak as found from the gain formula
is placed at one on the x axis
*/

photon1->Rebin(4);
photon2->Rebin(4);
photon3->Rebin(4);
// Rebin each histogram to eliminate "fencing"

float user_min = 0.5;
float user_max = 16;
// Sets the user min and max
// or where the user can see in the histogram

float extr_max = 30;
/* extr_max is the "extrapolation max" used
exclusively to determine the average photoelectrons
of each fit. 30 was selected because the
distributions used go to zero quite rapidly and thus
by 30 Photoelectrons the fit function is practically zero.
*/

float lowbound = photon1->GetXaxis()->FindFixBin(user_min);
// Declares upper and lower bounds for integration.

float upbound = photon1->GetXaxis()->FindFixBin(user_max);
/* Integration is used to normalize the histograms
in the users max and min view area.
Since integration is done between bin numbers and
not x-axis values, the x-axis values must first be converted
into bin numbers.
*/

Double_t IntGral = photon1->Integral(lowbound, upbound);
// Declares and defines the integral between the bins
// previously found

photon1->Sumw2();
photon1->Scale(1/IntGral);
/* Normalizes the histogram in the user region.

```

This must be done for each histogram seperately
since each histogram has different entries in
in the user region

*/

```
IntGral = photon2->Integral(lowbound, upbound);
```

```
photon2->Sumw2();
```

```
photon2->Scale(1/IntGral);
```

```
IntGral= photon3->Integral(lowbound, upbound);
```

```
photon3->Sumw2();
```

```
photon3->Scale(1/IntGral);
```

```
// Follows the same procedure as above for the other histograms
```

```
photon1->Draw("hist");
```

```
gStyle->SetHistLineColor(2);
```

```
photon2->UseCurrentStyle();
```

```
photon2->Draw("hist SAME");
```

```
gStyle->SetHistLineColor(4);
```

```
photon3->UseCurrentStyle();
```

```
photon3->Draw("hist SAME");
```

```
\* Draws each histogram on the canvas to the specified colour  
in order to avoid confusion between the histograms.
```

*/

```
photon1 -> GetXaxis()->SetRangeUser(user_min, user_max);
```

```
// Sets the user range of the histogram
```

```
photon1->GetYaxis()->SetRangeUser(0, 0.01);
```

```
// Limits the y-axis view of the user due to the height of the third  
// histogram which is "taller" than the other two.
```

```
photon1->SetTitle("Poisson Comparison of Materials Data");
```

```
// Sets the title of the particular histogram
```

```
photon1->GetXaxis()->SetTitle("Photoelectrons");
```

```
// Names the x-axis to Photoelectrons as per  
// the scale function called earlier
```

```
photon1->GetYaxis()->SetTitle("Normalized Events");
```

```
// Names the y-axis Normalized Events  
// as per the normalization done earlier
```

```
photon1->GetYaxis()->SetTitleOffset(1.4);
```

```
\* Formats the y-axis title such that the title
```

```

does not block any of the values written
on the y axis.
*/

float fit_min = 1.5;
float fit_max = 16.;
float num_par = 6;
/* Defines the particular fit variables, namely between
which x values the fit should be performed and
also the number of parameters used.
*/

TF1 *fit_function1 = new TF1("fit_function1", mult_pois1,
fit_min, fit_max, num_par);
// Defines the function to be fit to the first histogram

fit_init1(fit_function1);
// Function call to fit_init which initializes
// the parameters of the fit

photon1->Fit("fit_function1", "MREN");
/* Fits the histogram to the function defined previously
fit options are MREN:
M: Improved fit results
R: Use the range specified in the function range
E: Uses Minos to perform better error estimates
N: Do not store the graphics or draw the fit on the canvas
*/

c1->Update(); // Updates the canvas

TF1 *fit_function2 = new TF1("fit_function2", mult_pois2,
fit_min, fit_max, num_par);
// Defines the function to be fit to the second histogram

fit_init2(fit_function2);
// Initializes the parameters of the fit

photon2->Fit("fit_function2", "MREN");
// Fits the function, see above for options details

c1->Update(); // Updates the canvas

TF1 *fit_function3 = new TF1("fit_function3", mult_pois3,
fit_min, fit_max, num_par);
// Defines the function to be fit to the third histogram

```

```

fit_init3(fit_function3);
// Initializes the third set of parameters

photon3->Fit("fit_function3", "MREN");
// Fits the function, see above for options details

c1->Update(); // Update canvas

/*
The fit option "N" was selected specifically because the fit
would have to be extrapolated past the fit_max previously
defined. This extrapolation was done to determine the
average photoelectrons according to the fit, which was
presumably a useful quantity. Fit option "N" saves the
parameter values, but does not draw the fit on the histogram.
This allowed for the parameters to be recovered and then used
in the same function that was previously fit, but with the
extrapolated max, extr_max, as the upper limit.
*/

TF1 *pois1 = new TF1("pois1", "[0]*TMath::Poisson(x, [1])+
[2]*TMath::Poisson(x, [3])+[4]*TMath::Poisson(x, [5])",
fit_min, extr_max);

for(int i = 0; i < num_par; i++)
{
    pois1->SetParameter(i, fit_function1->GetParameter(i));
}
pois1->SetLineColor(1);
pois1->Draw("SAME");

/* The above is the recovery of the fit parameters and the setting of
equivalent parameters in a new function. The new function was the drawn
on the canvas c1 using option "SAME", allowing for the function to be
drawn over all of the other objects previously drawn. The parameters
in the function are given in square brackets. The for loop is used
to recover the parameters from the fit and then place those recovered
values into the parameters for the new function.
*/

c1->Update(); // Canvas update

TF1 *pois2 = new TF1("pois2", "[0]*TMath::Poisson(x, [1])+
[2]*TMath::Poisson(x, [3])+[4]*TMath::Poisson(x, [5])",

```

```

fit_min , extr_max);

for(int i = 0; i < num_par; i++)
{
    pois2->SetParameter(i, fit_function2->GetParameter(i));
}
pois2->SetLineColor(2);
pois2->Draw("SAME");

// Recovery of the second set of fit parameters.

c1->Update();

TF1 *pois3 = new TF1("pois3", "[0]*TMath::Poisson(x, [1])+
[2]*TMath::Poisson(x, [3])+[4]*TMath::Poisson(x, [5])",
fit_min , extr_max);

for(int i = 0; i < num_par; i++)
{
    pois3->SetParameter(i, fit_function3->GetParameter(i));
}
pois3->SetLineColor(4);
pois3->Draw("SAME");

// Recovery of the third set of fit parameters

c1->Update();

leg = new TLegend(0.8, 0.8, 1, 1);
// Defines the legend and the location of the legend on the canvas

/* The following add the entries to the legend,
which takes approximately the same position in
the canvas as the statistics box did. The legend is more
useful in this circumstance because it provides
information about which histogram/fit corresponds
to which coupling method used.
*/

leg->AddEntry(photon_plot1, "Grease", "l");
leg->AddEntry(photon_plot2, "Cookie", "l");
leg->AddEntry(photon_plot3, "Air Gap", "l");
leg->SetHeader("Legend");
leg->Draw();
c1->Update();

```

```

float chisqrd = fit_function1->GetChisquare();
float ndf = fit_function1->GetNDF();
// Defines variables to hold both the Chi^2 and the NDF

float chiperndf = chisqrd/ndf;
/* Takes the previously defined chi squared and NDF
and converts them into the reduced chi squared
(chi^2/NDF)
*/

cout << "The Chi Squared per NDF for Grease is: "
<< chiperndf << endl;
// Outputs this value to the user

chisqrd = fit_function2->GetChisquare();
ndf= fit_function2->GetNDF();
chiperndf = chisqrd/ndf;
// Produces the reduced chi squared for the second fit

cout << "The Chi Squared per NDF for RTV is: "
<< chiperndf << endl;
// Outputs the value to the user

chisqrd = fit_function3->GetChisquare();
ndf= fit_function3->GetNDF();
chiperndf = chisqrd/ndf;
// Produces the reduced chi squared for the third fit

cout << "The Chi Squared per NDF for Air Gap is: "
<< chiperndf << endl << endl;
// Outputs the value to ther user

float xMax1=fit_function1->GetMaximumX(user_min , user_max);
float xMax2=fit_function2->GetMaximumX(user_min , user_max);
float xMax3=fit_function3->GetMaximumX(user_min , user_max);

/* The above commands find the maximum in each of the
three fits and then determines which X value corresponds
to that maximum. This provides the peak photoelectrons for
the particular fit.
*/

cout << "The location of the peak in the Grease fit is: "
<< xMax1 << endl;

```



```

cout << "The location of the peak in the RTV fit is: "
<< xMax2 << endl;
cout << "The location of the peak in the Air Gap fit is: "
<< xMax3 << endl << endl;
// Outputs the three peak photoelectron values to the user

float Mean1 = pois1->Mean(user_min, extr_max);
float Mean2 = pois2->Mean(user_min, extr_max);
float Mean3 = pois3->Mean(user_min, extr_max);
// These commands determine the mean of the fit
// in the extrapolated region.

cout << "The average photoelectrons for each are:" << endl
<< "GREASE: " << Mean1 << endl << "RTV: "
<< Mean2 << endl << "AIR GAP: " << Mean3 << endl << endl;
// Outputs the means of each fit in the extrapolated region

return 0; // End of primary script.
}

Double_t mult_pois1(Double_t *x, Double_t *par)
// Declares the first fit function
{

Double_t result1 = par[0]*TMath::Poisson(x[0], par[1]);
Double_t result2 = par[2]*TMath::Poisson(x[0], par[3]);
Double_t result3 = par[4]*TMath::Poisson(x[0], par[5]);

return result1+result2+result3;

/* Each of these results is one of the three poisson distributions
used in the fit process. The source code of the TMath::Poisson
function can be found here:
http://root.cern.ch/root/html/src/TMath.cxx.html#gvSxE
The results are added together and returned to the main script.
*/

}

Double_t mult_pois2(Double_t *x, Double_t *par)
// Declares the second fit function
{

```

```

Double_t result1 = par[0]*TMath::Poisson(x[0], par[1]);
Double_t result2 = par[2]*TMath::Poisson(x[0], par[3]);
Double_t result3 = par[4]*TMath::Poisson(x[0], par[5]);

return result1+result2+result3;

// See comments above about the first fit function
}

Double_t mult_pois3(Double_t *x, Double_t *par)
// Declares the third fit function
{
Double_t result1 = par[0]*TMath::Poisson(x[0], par[1]);
Double_t result2 = par[2]*TMath::Poisson(x[0], par[3]);
Double_t result3 = par[4]*TMath::Poisson(x[0], par[5]);

return result1+result2+result3;

See the comments above about the first fit function
}

/* Fit init initializes the fit parameters by setting the
names of each parameter as well as by setting the initial
values of each parameter.
*/

int fit_init1 (TF1* fit_function1) {

fit_function1->SetParName(0,"Amplitude 1");
fit_function1->SetParName(1,"Mean 1");
fit_function1->SetParName(2,"Amplitude 2");
fit_function1->SetParName(3,"Mean 2");
fit_function1->SetParName(4,"Amplitude 3");
fit_function1->SetParName(5,"Mean 3");
//The above sets all the names of the
//parameters used in the first fit function.

fit_function1->SetParameter(0,0.03); //Initialize Amplitude #1
fit_function1->SetParameter(1,3.0); //Initialize Mean #1
fit_function1->SetParameter(2,0.03); //Initialize STDEV 1
fit_function1->SetParameter(3,5); //Initialize Amp. 2
fit_function1->SetParameter(4,0.03); //Initialize mean 2

```

```
fit_function1->SetParameter(5,9); //Initialize STDEV 2
// The above sets all of the initial values for the parameters

fit_function1->SetLineColor(1); // Selects line colour
fit_function1->SetLineWidth(2.); // Selects line width

}

int fit_init2 (TF1* fit_function2) {
// Second fit initialization function

//fit_function->SetNpx(2000);

// Sets the names of the parameters used in the fit

fit_function2->SetParName(0,"Amplitude 1");
fit_function2->SetParName(1,"Mean 1");
fit_function2->SetParName(2,"Amplitude 2");
fit_function2->SetParName(3,"Mean 2");
fit_function2->SetParName(4,"Amplitude 3");
fit_function2->SetParName(5,"Mean 3");

fit_function2->SetParameter(0,0.03); //Initialize Amplitude #1
fit_function2->SetParameter(1,3.0); //Initialize Mean #1
fit_function2->SetParameter(2,0.03); //Initialize STDEV 1
fit_function2->SetParameter(3,5); //Initialize Amp. 2
fit_function2->SetParameter(4,0.03); //Initialize mean 2
fit_function2->SetParameter(5,9); //Initialize STDEV 2

// The above sets all of the initial values for the parameters

fit_function2->SetLineColor(1); // Selects line colour
fit_function2->SetLineWidth(2.); //Selects line width

}
```

```

int fit_init3 (TF1* fit_function3) {

    // Third fit initialization function

    //fit_function->SetNpx(2000);

    // Sets the names of the parameters used in the fit

    fit_function3->SetParName(0,"Amplitude 1");
    fit_function3->SetParName(1,"Mean 1");
    fit_function3->SetParName(2,"Amplitude 2");
    fit_function3->SetParName(3,"Mean 2");
    fit_function3->SetParName(4,"Amplitude 3");
    fit_function3->SetParName(5,"Mean 3");

    fit_function3->SetParameter(0,0.03); //Initialize Amplitude #1
    fit_function3->SetParameter(1,3.0); //Initialize Mean #1
    fit_function3->SetParameter(2,0.03); //Initialize STDEV 1
    fit_function3->SetParameter(3,5); //Initialize Amp. 2
    fit_function3->SetParameter(4,0.03); //Initialize mean 2
    fit_function3->SetParameter(5,9); //Initialize STDEV 2

    // The above sets all of the initial values for the parameters

    fit_function3->SetLineColor(1); // Selects line colour
    fit_function3->SetLineWidth(2.); //Selects line width

}

/* The following functions were taken from the Root forums located at:
http://root.cern.ch/phpBB3/viewtopic.php?f=3&t=12344
These functions scale the X axis linearly.
*/

Double_t ScaleX(Double_t x)
{
    Double_t v;
    Double_t Sfactor = 1/67.43;

```

```

// Scale Factor chosen so first peak in data is
// at 1 on the new X axis, found from the gain formula

v = Sfactor * x; // "linear scaling" function example
return v;
}
void ScaleAxis(TAxis *a, Double_t (*Scale)(Double_t))
{
    if (!a) return; // just a precaution
    if (a->GetXbins()->GetSize())
    {
        // an axis with variable bins
        // note: bins must remain in increasing order, hence the "Scale"
        // function must be strictly (monotonically) increasing
        TArrayD X(*(a->GetXbins()));
        for(Int_t i = 0; i < X.GetSize(); i++) X[i] = Scale(X[i]);
        a->Set((X.GetSize() - 1), X.GetArray()); // new Xbins
    }
    else
    {
        // an axis with fix bins
        // note: we modify Xmin and Xmax only, hence the "Scale" function
        // must be linear (and Xmax must remain greater than Xmin)
        a->Set(a->GetNbins(),
            Scale(a->GetXmin()), // new Xmin
            Scale(a->GetXmax())); // new Xmax
    }
    return;
}

void ScaleXaxis(TH1 *h, Double_t (*Scale)(Double_t))
{
    if (!h) return; // just a precaution
    ScaleAxis(h->GetXaxis(), Scale);
    return;
}

```