Development of a Gain Monitoring System for a Neutron Detector Array

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in the Partial Fulfillment of the Requirements for the Degree of Master of Science in the Department of Physics and Engineering Physics University of Saskatchewan Saskatoon

by

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Abstract

The Blowfish neutron detector array contains 88 detectors arranged in a spherical geometry that covers a solid angle of approximately $\frac{1}{4}$ of $4\pi$ sr. Blowfish’s large angular acceptance and excellent angular resolution makes it ideal for the study of nuclear reactions where a neutron is to be detected in the final state. Such measurements are needed for the study of the Gerasimov-Drell-Hearn sum rule for the deuteron and few-body physics through photo-disintegration.

The relationship between the energy deposition in an detector by a incident particle and the signal read out by a data acquisition system is characterized by a quantity known as the gain. The gain, once established by calibration, may drift over time. To improve the neutron detector array a gain monitoring system will be included. The new system will provide continuous information about the gain of all 88 detectors on the array simultaneously. This can be achieved using a stable light emitting diode (LED) light source and a fiber optic network distributing the light to the detectors. Measurements are taken of the LED light by the Blowfish array and four LED monitoring detectors. These four monitoring detectors also have a radioactive source placed between them to give a continuous reference calibration. Once the absolute gain of the array is measured, the LED light and the LED monitor detectors allow changes in gain to be tracked for the 88 detectors on the array.

Several system tests were conducted to determine the accuracy of the gain monitoring system. Three groups of trials focused on the effects of voltage drifts in the high voltage supply to the Blowfish detector photomultiplier tubes, the LED monitor detector photomultiplier tubes, and in the LED driving voltage. The results of the systems tests conclude that the gain monitoring system can accurately track the detector gains. The calculated error in the detector efficiency for neutron energies of 6 and 10 MeV with the measured gain uncertainties was less then 1 % for all tested voltage drifts when the detector signal thresholds were between 100 and 500 keV.
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<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>BNC</td>
<td>Berkeley Nucleonics Corporation</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>DFELL</td>
<td>Duke Free Electron Laser Laboratory</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>GDH</td>
<td>Gerasimov-Drell-Hearn</td>
</tr>
<tr>
<td>HIGS</td>
<td>High Intensity Gamma Source</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>PAW</td>
<td>Physics Analysis Workstation</td>
</tr>
<tr>
<td>PM</td>
<td>Photomultiplier</td>
</tr>
<tr>
<td>PMT</td>
<td>Photomultiplier Tube</td>
</tr>
<tr>
<td>PSD</td>
<td>Pulse Shape Discrimination</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>TDC</td>
<td>Time to Digital Converter</td>
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Chapter 1

Introduction

1.1 Background

In experimental physics data are commonly collected by detecting particles. A particle is detected by depositing some or all of its energy in a detector volume. This deposited energy can often be small and hence a method of amplifying this energy is needed to create an observable signal. A common method of amplifying the energy deposited by a particle to a level where electronic systems can process the signals is to use a scintillator and photomultiplier. In this amplification process it is essential to know the relation between the magnitude of the detector’s electronic output pulse, and the energy that the particle deposited in the scintillator. This quantity is called gain and in general it is necessary to know the gain when analyzing data to extract meaningful results. If the detector gain is not known accurately then the calculation of the detector efficiency and the reaction cross section will be inaccurate. However it is often the case that the gain is subject to change over time. This thesis examines a method of tracking gain changes and includes discussions on the design, construction, and testing of the gain monitoring system.
1.1.1 Experiments

During experiments the quantity measured is the number of reaction product particles detected. It is therefore important to be able to relate the number of particles measured to the probability of the measured process occurring. In a typical nuclear reaction an incident particle, with energy $E$, impinges on a nucleus. The result is a product particle which exits from the reaction at angles $\theta$ and $\phi$ as defined in figure 1.1. The differential cross section is a quantity that gives as a function of incident particle energy and reaction product particle angle, the probability of reaction between an incident flux of particles and the target on which they are impinging. The total cross section for a given incident particle energy $E$ over all reaction product angles may be written as

$$
\sigma(E) = \int d\Omega \frac{d\sigma(E, \theta, \phi)}{d\Omega}.
$$

(1.1)

Where, $\frac{d\sigma(E, \theta, \phi)}{d\Omega}$, is the differential cross section. The unit of the cross section is the barn which is equal to $10^{-24}\text{cm}^2$. The average number of reaction product particles scattered into the solid angle $d\Omega$ is $N_s$ and is defined as [Leo94]

$$
N_s(\Omega) = F_{\text{tot}} N \delta x \frac{d\sigma}{d\Omega}.
$$

(1.2)

where $\delta x$ is the target thickness along the beam axis, $N$ the density of target centers in atoms cm$^{-3}$, and $F_{\text{tot}}$ the total incident number of particles, which is the time integrated particle flux, $F$, given in particles sec$^{-1}$. If all angles are considered the total cross section is,

$$
d\sigma = \frac{N_s(\Omega)}{F_{\text{tot}} N \delta x} d\Omega \implies \int d\sigma = \int \frac{N_s(\Omega)}{F_{\text{tot}} N \delta x} d\Omega \implies \sigma_{\text{tot}} = \frac{N_{\text{tot}}}{F_{\text{tot}} N \delta x}.
$$

(1.3)

It should be noted that the above formula for the cross section is in a simple form which does not take into account experimental factors that need to be considered like detector efficiencies or dead time. Equation 1.3 would be scaled by factors to correct for these aspects. The gain monitoring system presented in this thesis is designed to allow the detector efficiency factor to be determined.
The following are some examples of studies that require accurate measurements of the reaction cross section. Measurements of the $d(\gamma, n)p$ asymmetry using linearly polarized gamma rays has been done at the HIGS facility in 2001, 2003, and 2005 with additional measurements planned for the future. Planned for the near future are measurements of $^4\text{He}$ few body photoneutron cross-section, $^4\text{He}(\gamma, n)$. Another future experiment is the measurement of the Gerasimov-Drell-Hern (GDH) sum rule. The GDH sum rule relates the photodisintegration cross-sections of circularly polarized gamma rays on a polarized target when the spins are parallel ($\sigma_P$) and when they are anti-parallel ($\sigma_A$), as shown in Figure 1.2, over energies from a threshold to infinity.[Are00]

\[ \int_{\omega_X}^{\infty} \frac{\sigma_A - \sigma_P}{\omega} d\omega = 2\pi^2 \alpha S_l \left( \frac{\kappa_l}{m_l} \right)^2 \]

Figure 1.2: Parallel (left) and anti-parallel (right) helicities and polarizations.
\[ = -204.0 \mu b \text{(proton)}, -232.0 \mu b \text{(neutron)} \]

GDH sum rule for the deuteron:

\[
\int_{\omega_d}^{\omega} \frac{\sigma_A - \sigma_P}{\omega} d\omega = 2\pi^2 \alpha S_d \left( \frac{\kappa_d}{m_d} \right)^2 = -0.6 \mu b \text{(deuteron)}
\]

The deuteron looks like a loosely bound proton and neutron at higher energies above pion threshold:

\[
\int_{\omega_d}^{\omega_d\pi} \frac{\sigma_A - \sigma_P}{\omega} d\omega + \int_{\omega_d\pi}^{\omega} \frac{\sigma_A - \sigma_P}{\omega} d\omega = -0.6 \mu b
\]

\[
\int_{\omega_d}^{\omega_d\pi} \frac{\sigma_A - \sigma_P}{\omega} d\omega + (-204.0 \mu b - 232.0 \mu b) \approx -0.6 \mu b
\]

\[
\Rightarrow \int_{\omega_d}^{\omega_d\pi} \frac{\sigma_A - \sigma_P}{\omega} d\omega \approx 436 \mu b
\]

- \( \kappa_l \) - anomalous magnetic moment of the target particle
- \( m_l \) - mass of the target particle
- \( \omega_{\pi} \) - pion threshold (\( \approx 140 \) MeV)
- \( \omega_d \) - deuteron disintegration threshold (\( \approx 2.2 \) MeV)
- \( S_l \) - spin of the target particle

This deuteron sum rule provides a consistency check of the nucleon sum rules. Any discrepancy found could be attributed to the nucleon sum rules, particularly our understanding of the internal dynamics. It should be noted that the majority of the integral’s magnitude in the GDH sum rule for the deuteron lies below 20 MeV. To find any deviation from theory, and to distinguish between similar nuclear model predictions, absolute cross section measurements using a detector array like \textit{Blowfish} are necessary with gain errors less than 1 \%.
The facility needed to perform the GDH sum rule and the $^4$He photodisintegration experiments must have a high incident $\gamma$-ray flux, so that data acquisition rates and the signal to noise ratio (SNR) are acceptable, and be capable of producing polarized $\gamma$-rays in the needed energy range. As well a detector system capable of detecting neutrons is needed at the facility.

1.1.2 Experimental Facility

The High Intensity Gamma Source (HIGS) is located at Duke University in North Carolina and is well suited for a wide range of $\gamma$ energies and can deliver high fluxes. Figure 1.3 shows the general layout of the facility and future expansions planned for HIGS.

![Figure 1.3: HIGS $\gamma$ ray producing apparatus.](image)

The facility can produce a $\gamma$-ray flux of $10^6 - 10^7$ photons/sec. With the current configuration of
the facility γ rays are produced linearly polarized along the horizontal (y) axis. The γ-ray energy range of the facility will be 2.0 – 225 MeV after the booster injector upgrade is complete. For any given energy the γ-rays produced are monochromatic ($\frac{\Delta E}{E} \approx 1\%$). It was with this γ-ray source that the previous d(γ, n)p asymmetry experiment was done using the neutron detector known as Blowfish.

1.1.3 Blowfish Detector Array

The array called Blowfish is a neutron detector which covers a solid angle of $\approx \frac{1}{4} 4\pi$ sr. There are 8 uniformly spaced arms that make up the array, which can rotate about the beam axis in the $\phi$ direction. On each arm there are 11 uniformly spaced cells on the surface of a 16 inch radius sphere covering polar angles from $\theta = 22.5^\circ$ to $\theta = 157.5^\circ$ (See Figure 1.4). The Large solid angle coverage of the array makes it ideal for few-body experiments where reaction products have varying angular dependence. Furthermore the ability to rotate the array about the beam axis allows accurate determination of instrumental systematic effects.

The detectors on Blowfish are made of three main components: a scintillator, a light guide, and a Photomultiplier Tube (PMT). The scintillator cell is a Lucite box $8.2 \text{ cm} \times 8.2 \text{ cm} \times 7.1 \text{ cm}$ with 0.3 cm thick walls. The cells are filled with BC-505 liquid scintillator. The scintillator functions as a way to convert the kinetic energy of incident particles into light. The total scintillator active volume is $7.6 \times 7.6 \times 6.5 \text{ cm}^3$. Each cell is optically coupled to a 12-stage Phillips XP2262B PMT through a 4.5 cm Lucite light guide and a $\approx 0.5$ cm silicone “cookie”. Each detector is made light tight so that only light originating in the BC-505 scintillator can reach the PMT. The BC-505 scintillator was chosen because it allows pulse shape discrimination (PSD), a technique used to differentiate between different particles. BC-505 detects neutrons by giving off scintillation light when energetic neutrons inelastically collide with protons in the BC-505 scintillator. Figure 1.5
shows a plot of proton kinetic energy deposited in the scintillator for a neutron energy of 10 MeV. A complete description of the interaction of particles with matter leading to the emission of scintillation light will be given in section 2.2. Also in Figure 1.5 is a plot of the resulting scintillation light output of BC-505 for the energy deposition shown in the figure beside it. The light output is given in units of the light output from an electron of equivalent energy MeV\textsubscript{ee}. It is this light that is detected by the PMT and amplified to give a measurable detector signal. The process by which the PMT amplifies the scintillation light output to give a usable signal, and the general design of a PMT is discussed in the next section.

### 1.1.4 Photomultiplier Tubes

In a scintillator-photomultiplier system the energy deposited by the particle in the scintillator causes scintillation light to be given off. This scintillation light is then collected and impinges on the photocathode of the photomultiplier tube (PMT). The photocathode uses the photoelectric effect to convert the light from the scintillator into a current of electrons. This necessitates that the
Figure 1.5: The energy deposited by a neutron in the BC-505 scintillator produces light that is expressed in terms of an electron’s light output for comparison.

The scintillator chosen must emit light with an energy above that of the photocathode work function for any photoelectrons to be produced. This process is described by Einstein’s formula

$$E = h\nu - \phi,$$

(1.4)

where $E$ is the resulting kinetic energy of the photoelectron, $\nu$ the frequency of the impinging scintillation light, and $\phi$ the work function of the photocathode material.

Once scintillation light is converted into a current of electrons they are collected and accelerated by a focusing electrode and go on to the multiplier section of the PMT. The multiplier consists of several dynode stages. Incident electrons from the photocathode strike the dynode transferring energy to electrons in the dynode. The transfer of energy causes secondary electrons to be emitted, which are then accelerated toward the next stage in the dynode chain where the process of collision and release of secondary electrons is repeated. This process occurs down the entire dynode chain in a mechanism described as cascading. At the anode the electron cascade is collected to give a current which can be analyzed (See Figure 1.6).
Figure 1.6: Basic design of a photomultiplier tube.

The amplification factor or gain of a PMT depends on two factors. The number of dynodes in the multiplier section, and the amount of secondary electrons emitted after an incident electron collides into the dynode. The latter of the two factors is a function of energy and is given the symbol $\delta$. In the dynode chain the incident electron energy depends on the potential difference between the dynodes, $V_{\text{dynode}}$. The secondary emission factor can be written as

$$\delta = KV_{\text{dynode}},$$  \hspace{1cm} (1.5)$$

where $K$ is a proportionality constant.[Leo94] If the voltage is equally divided among the $n$ dynodes of the PMT the total gain is

$$G = \delta^n = (KV_{\text{dynode}})^n.$$  \hspace{1cm} (1.6)$$

It should be noted that due to the power relationship a twelve stage PMT will have a significant change in gain for even small changes in applied voltage. It is therefore important to monitor any
change in the PMT gain.

Gain drift is considered to be the variation of the gain under constant illumination. The primary cause of drift is fatigue effects somewhere in the PMT system. To test for PMT gain drift a known energy peak from a radioactive source can be monitored. Care should be taken not to cause signal pile up during the measurement. This is where signals are so frequent that the detector has not finished firing from one event when another occurs. In general if $\tau$ is the decay constant of the detector pulses the count rate should not exceed $1/\tau$. The PMT should operate for a few hours with a constant count rate to allow the gain to stabilize. Following the initial stabilizing period the position of the known energy peak is determined for the constant count rate. The drift is given by [Leo94]

$$\text{Drift} = \frac{\sum |\bar{P} - P_i|}{nP},$$  

(1.7)

where $P_i$ is the peak position of the $i$th measurement, $n$ the number of measurements, $\bar{P}$ the average of $P_i$. An acceptable PMT gain drift is $\leq 1\%$.

From equations 1.5 and 1.6 above the two possible changes that can lead to drift are differences in the dynode voltage $V_{\text{dynode}}$, or the dynode proportionality constant $K$. The power supply used in the current experiment at HIGS is accurate to 1 Volt. The voltage from the power supply is split between the different dynodes evenly. For a Phillips XP2262B twelve stage photomultiplier tube the error in voltage for a dynode is $\frac{1}{12}$ V. For a low PMT operating voltage of 1500 V, where the 1 V uncertainty will have the largest effect on the gain, the corresponding dynode voltage is 125 Volts. The difference in gain from a 1 Volt change is,

$$\frac{G'}{G} \propto \frac{V'}{V} = \frac{(125 - 1/12)^{12}}{125^{12}} = 0.992$$
The calculation above demonstrates that gain drift from the voltage supply will contribute < 1% error to the gain value. The remainder of the gain drift is associated with change in the dynode constant K. A small change in the dynode constant can have a large effect on the gain value. A typical value for a XP2262B dynode constant is \( \simeq 2.86 \times 10^{-2} \). If the dynode constant changes by 1% the gain value is affected by over 10%.

\[
\frac{G'}{G} \propto \frac{K'}{K} = \frac{(0.0286 \times 0.99)^{12}}{0.0286^{12}} = 0.886
\]

Even small dynode constant changes, \( \approx 0.1\% \), will cause gain changes over 1%.

\[
\frac{G'}{G} \propto \frac{K'}{K} = \frac{(0.0286 \times 0.999)^{12}}{0.0286^{12}} = 0.988
\]

Hence the majority of gain drift will be from fatigue and aging effects of the phototube. The standard way of tracking phototube aging effects is with repeated measurements of a known radioactive source.

### 1.1.5 Gain Tracking

Due to the number of detectors on the Blowfish array gain monitoring using radioactive sources is very time consuming. The radioactive source must be placed near each detector cell long enough for suitable statistics to be obtained for Compton edge finding or particle capture peak fitting, depending on the source used. Another draw back is that gain monitoring with a radioactive source uses valuable experimental beam time as it can only be done when the facility is not providing a \( \gamma \)-ray flux. Thus in the past PMT gains have only been measured at the beginning and the end of a day of experimentation. A more efficient and thorough way to monitor the gain is to acquire gain monitoring data simultaneously for all detector cells during the experiment. This can be achieved using a stable light source which is monitored, and an optical network connecting the light source to the detectors.[Nom00] Once the initial absolute gain has been determined using a radioactive
source relative changes in the individual PMTs are measured using the light emitting diode (LED) light source within the gain monitoring system. [Koz00] There are few published papers with gain monitoring data, however some technical documents are available with gain monitoring system designs for other experiments. The use of LED light and a fiberoptic network is the most common technique for monitoring a large number of detectors simultaneously. [Kha98] Figure 1.7 outlines the proposed LED gain monitoring system. The main components of the monitor are the pulser, the LEDs with housings, LED monitor detectors and the fiber optic bundle.

![Proposed gain monitor design.](image)

A typical experiment would proceed as follows. The absolute gains of the Blowfish detectors would be measured using a radioactive source. Figure 1.8 shows a typical set of histograms from a Blowfish gain measurement. During the radioactive source measurement the position of the LED peak would also be measured and histogramed. The Compton edge feature of the Blowfish detector can be seen in the upper left diagram in Figure 1.8 at a position of about 2500. The position of this known energy feature is used for the initial calibration the detector. Once the experiment has begun, with no reference source in the Blowfish array, gain changes are measured
by the relative movement of the LED light peak. To ensure any movement of the LED peak is due to gain drift and not light intensity changes each LED will be monitored by a detector. The LED monitor detector will measure the LED peak and a radioactive source continuously. The lower left diagram in Figure 1.8 shows the radioactive source spectra for the monitor detector. The second peak centered around 2300 is the full energy peak of the known radioactive source and is used for detector calibration and to monitor for gain shifts. With the initial values of both the Blowfish array and the monitor detectors, the continuous LED measurements from both the Blowfish array and the monitor detectors, as well as the reference source information from the monitor detectors, the gains of the Blowfish detectors can be determined for the second data acquisition session. The gain monitoring formulae will now be derived. All of the variable definitions for the following derivation are in Tables 1.1 and 1.2.

Table 1.1: Gain correction definitions (Units of all variables in ADC channel number).

| Sourceb1,2 | Source peak position in a Blowfish detector during a source calibration session, (1) or (2), with a peak energy of E_{gb} |
| Sourcem1,2 | Source peak position in a monitor detector during a source calibration session, (1) or (2), with a peak energy of E_{gm} |
| LEDb1,2  | LED light source peak position in a Blowfish detector during a source calibration session, (1) or (2). |
| LEDm1,2  | LED light source peak position in a monitor detector during a source calibration session, (1) or (2). |

For the monitor detectors the gain of the detectors during the two different measurements is equal to the reference energy divided by the ADC bin number location where the reference energy appears,
Figure 1.8: Standard histogram information for gain tracking. The top left figure shows the calibration spectra that would be collected by the *Blowfish* array prior to the experiment. The top right figure shows the LED peak data that is acquired throughout the calibration measurement and the experiment. The bottom rows shows the same data for the LED monitor detector which is acquired through both the calibration and the experiment.

or the brightness of the LED light divided by the ADC peak location of the light pulse.

\begin{equation}
\begin{align*}
g_{m1} &= \frac{E_{\gamma m}}{\text{Source}_{m1}} = \frac{B_{m1}}{\text{LED}_{m1}} \\
g_{m2} &= \frac{E_{\gamma m}}{\text{Source}_{m2}} = \frac{B_{m2}}{\text{LED}_{m2}}
\end{align*}
\end{equation}

Using the equations above and taking the ratio of the monitor detector gains for the first and the second measurements gives,
Table 1.2: Gain correction definitions.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\gamma m}$</td>
<td>The calibration energy of the monitor detectors.</td>
</tr>
<tr>
<td>$E_{\gamma b}$</td>
<td>The calibration energy of the Blowfish detectors.</td>
</tr>
<tr>
<td>$g_{m1,2}$</td>
<td>The gain of the monitor detector during a measurement session, (1) or (2).</td>
</tr>
<tr>
<td>$g_{b1,2}$</td>
<td>The gain of the Blowfish detector during a measurement session, (1) or (2).</td>
</tr>
<tr>
<td>$B_{m1,2}$</td>
<td>The LED light reaching the monitor detector during a measurement session, (1) or (2).</td>
</tr>
<tr>
<td>$B_{b1,2}$</td>
<td>The LED light reaching the Blowfish detector during a measurement session, (1) or (2).</td>
</tr>
</tbody>
</table>

\[
\frac{g_{m1}}{g_{m2}} = \frac{\text{Source}_{m2}}{\text{Source}_{m1}} = \frac{\text{LED}_{m2}}{\text{LED}_{m1}} \times \frac{B_{m1}}{B_{m2}}
\]

\[
\Rightarrow \frac{B_{m1}}{B_{m2}} = \frac{\text{Source}_{m2}}{\text{Source}_{m1}} \times \frac{\text{LED}_{m1}}{\text{LED}_{m2}}
\]

Applying the same process above to the Blowfish detectors we arrive at similar formulae for the detector gains and LED brightness.

\[
g_{b1} = \frac{E_{\gamma b}}{\text{Source}_{b1}} = \frac{B_{b1}}{\text{LED}_{b1}}
\]

\[
g_{b2} = \frac{E_{\gamma b}}{\text{Source}_{b2}} = \frac{B_{b2}}{\text{LED}_{b2}}
\]
\[\frac{g_{b1}}{g_{b2}} = \frac{\text{Source}_{b2}}{\text{Source}_{b1}} = \frac{\text{LED}_{b2}}{\text{LED}_{b1}} \times \frac{B_{b1}}{B_{b2}}\]

\[\Rightarrow \frac{B_{b1}}{B_{b2}} = \frac{\text{Source}_{b2}}{\text{Source}_{b1}} \times \frac{\text{LED}_{b1}}{\text{LED}_{b2}}\]

Normally the brightness of the LED will not change from measurement to measurement. If it does change however it is assumed that the brightness going through different fibers in the same bundle will remain proportional.

\[\frac{B_{b1}}{B_{m1}} = \frac{B_{b2}}{B_{m2}}\] (1.11)

During the standard operation of the Blowfish array the second source measurement is not available to determine the detector gain. Another way of calculating the gain for the second data acquisition session is possible however, using the other known values.

\[\frac{g_{b1}}{g_{b2}} = \frac{\text{LED}_{b2}}{\text{LED}_{b1}} \times \frac{B_{b1}}{B_{b2}} = \frac{\text{LED}_{b2}}{\text{LED}_{b1}} \times \frac{B_{b1}}{B_{b1} \frac{b_{m2}}{b_{m1}}} = \frac{\text{LED}_{b2}}{\text{LED}_{b1}} \times \frac{B_{m1}}{B_{m2}}\]

\[\Rightarrow g_{b2} = g_{b1} \times \frac{B_{m2}}{B_{m1}} \times \frac{\text{LED}_{b1}}{\text{LED}_{b2}} = g_{b1} \times \frac{\text{Source}_{m1}}{\text{Source}_{m2}} \times \frac{\text{LED}_{m2}}{\text{LED}_{m1}} \times \frac{\text{LED}_{b1}}{\text{LED}_{b2}}\] (1.12)

\[\Rightarrow \frac{E_{fb}}{\text{Source}_{b2}} = \frac{E_{fb}}{\text{Source}_{b1}} \times \frac{\text{Source}_{m1}}{\text{Source}_{m2}} \times \frac{\text{LED}_{m2}}{\text{LED}_{m1}} \times \frac{\text{LED}_{b1}}{\text{LED}_{b2}}\]

\[\Rightarrow \text{Source}_{b2} = \text{Source}_{b1} \times \frac{\text{Source}_{m2}}{\text{Source}_{m1}} \times \frac{\text{LED}_{m1}}{\text{LED}_{m2}} \times \frac{\text{LED}_{b2}}{\text{LED}_{b1}}\]
Table 1.3: Gain correction formulae for detector calibration calculations.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED Correction Factor</td>
<td>$\text{LED}_{b2} \cdot \frac{\text{LED}_{m1}}{\text{LED}_{m2}} \cdot \frac{\text{Source}_{m2}}{\text{Source}_{m1}}$</td>
</tr>
<tr>
<td>Blowfish LED Peak Change</td>
<td>$\frac{\text{LED}_{b2}}{\text{LED}_{b1}} \cdot \frac{\text{LED}_{m1}}{\text{LED}_{m2}} \cdot \frac{\text{Source}_{m2}}{\text{Source}_{m1}}$</td>
</tr>
<tr>
<td>Blowfish Reference Peak Correction</td>
<td>$\text{Source}_{b1} \cdot \frac{\text{LED}_{b2}}{\text{LED}_{b1}} \cdot \frac{\text{LED}_{m1}}{\text{LED}_{m2}} \cdot \frac{\text{Source}_{m2}}{\text{Source}_{m1}}$</td>
</tr>
<tr>
<td>Blowfish ADC Gain</td>
<td>$\frac{E_{\phi}}{\text{Source}_{b1} \cdot \frac{\text{LED}_{b2}}{\text{LED}_{b1}} \cdot \frac{\text{LED}_{m1}}{\text{LED}_{m2}} \cdot \frac{\text{Source}_{m2}}{\text{Source}_{m1}}}$</td>
</tr>
</tbody>
</table>

The formulae from Table 1.3 will be used in an example of gain monitoring. Figure 1.9 shows a starting measurement of the LED peak position and the absolute gains using a radioactive source (1). At a later time when there is no reference source with the *Blowfish* array the LED peak position is measured while the monitor detector still has both peaks (2). In this example the LED intensity does not change during the two measurements, however the gain shifts on both the monitor detector and the *Blowfish* detector. Table 1.4 has the calculations for the test case.

1.1.6 Motivation

The importance of knowing the detector gain is that the experimenter can determine where the hardware threshold is and thus calculate the detector efficiency. In the example the gain change is from 1.655 $\text{keV}\text{bin}$ to 1.765 $\text{keV}\text{bin}$. Knowing this gain value allows the efficiency of the detector to
Figure 1.9: A schematic representation of gain tracking. The radioactive source positions and the LED peak positions from the calibration measurement (1) are used later during the experiment (2) to determine the Blowfish detector gain when a radioactive source location is not available.  

be determined, which is then used to calculate the cross section for the measured reaction. An example of this process is shown in Figure 1.10. The figure shows all the light that is produced by monoenergetic neutrons depositing energy in a BC-505 scintillator. Also on the figure are two threshold lines one low and one high. In a given experiment only those neutron events that are above the hardware threshold are detected by the system. This fraction of events above the threshold will determine the detector efficiency. In the example the gain changes from 1.655 keV\text{bin} to 1.765 keV\text{bin}. This would change the position of the threshold cut from a lower value to a higher one. Thus there would be more neutrons detected above the threshold line for 1.655 keV\text{bin} than there is for the higher threshold line. If the experimenter was not aware of this change then the total number of events entered into the cross section calculation (Equation 3) would be low, resulting in
Table 1.4: Gain monitor test case.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Calculation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected LED Peak Location</td>
<td>$750 \cdot \frac{1000}{900} \cdot \frac{450}{500}$</td>
<td>750 bins</td>
</tr>
<tr>
<td>Change in Blowfish LED Peak</td>
<td>$\frac{750}{800} \cdot \frac{1000}{900} \cdot \frac{450}{500}$</td>
<td>0.9375</td>
</tr>
<tr>
<td>Blowfish Reference Peak Correction</td>
<td>$\frac{400 \cdot 750}{800} \cdot \frac{1000}{900} \cdot \frac{450}{500}$</td>
<td>375 bins</td>
</tr>
<tr>
<td>Corrected Blowfish ADC Gain</td>
<td>$\frac{662 \text{ keV}}{400}$</td>
<td>$1.765 \text{ keV/bin}$</td>
</tr>
<tr>
<td>Original Blowfish ADC Gain</td>
<td>$\frac{662 \text{ keV}}{400}$</td>
<td>$1.655 \text{ keV/bin}$</td>
</tr>
</tbody>
</table>

a lower cross section estimated for that reaction. Similarly if the gain change went the other way the cross section would be larger than it should be. Thus it is important to determine accurately the detector gain if reliable detector efficiencies are to be calculated as well as accurate cross sections.

The following chapters document the design, development, and testing of a gain monitoring system. Theoretical background material on the gain monitor components and their functions will be reviewed. The theories of particle detection and signal processing will also be covered. After the development and construction of the gain monitoring system has been revealed the testing results will be given in the last discussion.
Figure 1.10: Light output threshold lines for 10 MeV neutrons.
Chapter 2

Theory

2.1 Theoretical Background

A review of the physical principles involved with the gain monitoring system and Blowfish will be conducted to guide project development. The review will include the underlying physics of detectors used in the experiment, as well as the theory behind each major component of the gain monitoring system.

The major areas of review are,

- **Interaction of Radiation Through Matter**

To understand how gain tracking of the Blowfish detectors work one must first understand how a scintillator absorbs the kinetic energy of incident particles. The primary mechanism that converts kinetic energy of particles into detectable light is the Coulomb interaction. If the incident particle is charged then it will interact with the atomic electrons directly. If the incident particle is not charged then it will interact with the atomic electrons indirectly. γ-rays would interact by Compton scattering, either once or with multiple scattering, or the photoelectric effect. The energy
transferred to the electron would then be deposited in the detector by Coulomb interactions with other atomic electrons. Neutrons in a hydrogen rich detector would collide with a proton. That recoil proton would travel through the cell depositing its kinetic energy through the Coulomb interaction. In all these cases charged particles leave atomic electrons in excited states or ionizes the atom. The subsequent deexcitations of these atoms produces the scintillation light which is guided to the PMT for amplification. Each of the particle interactions with matter discussed above will be described in more detail in the following discussions.

- **P-N Junctions**

The gain monitoring system design is dependent upon finding a fast pulsing light source that matches closely the scintillation light of BC-505. The light source chosen for the gain monitoring system is a Light Emitting Diode (LED). The properties of LEDs are well suited for the gain monitoring system because of the fast response and wavelength choices afforded by P-N junctions. These properties of P-N junctions will be discussed in the following sections.

- **Optic Waveguides**

For the gain monitor design to operate properly a reliable optical waveguide for the pulsed light is needed. A necessary waveguide property is large light collection to ensure a measureable amount of light reaches the photocathode of the PMTs. The various physical properties that govern how a optical waveguide collects and transports light will be discussed in the following sections.

- **Pulse Shape Discrimination**

One of the important methods of event processing where particle type is determined is pulse shape discrimination (PSD). The use of PSD during Blowfish experiments allows neutron detection data to be separated from $\gamma$-rays and electrons. The gain monitor light pulses must work in parallel with this system conforming to the electronic timing restrictions set by the PSD circuit. The principles
of PSD will be reviewed in the following sections so that the processes and restrictions associated with this detection technique are understood.

Each of the areas listed above will subsequently be investigated in order.

2.2 Interaction of Radiation Through Matter

There are many types of radiation produced during a subatomic physics experiment and every type interacts differently with matter. In the following sections the passage of radiation through matter will be discussed for the most common forms of radiation. It is important to know how various types of radiation interact with matter to understand how the scintillator will absorb kinetic energy and which radiation processes are significant contributors to the detector signal. The scintillator in question is BC-505 which is comprised of hydrogen and carbon with a mixing ratio of $\text{H} : ^{12}\text{C} = 1.331 : 1$ and a density of 0.877 g/cm$^3$.

2.2.1 Interactions of Heavy Charged Particles with Matter

The passage of heavy charged particles through matter can be summarized by a list of interactions resulting in energy loss by the incident heavy charged particle. It should be noted that in this discussion heavy charged particles refer to those particles heavier than the electron up to the light nuclei and atomic ions. For example this category would contain muons, pions, $\alpha$-particles and other light nuclei. The interactions of these particles through matter have two primary processes of energy loss:

- inelastic collisions with atomic electrons of the material
- elastic scattering from nuclei
The formula which gives the rate of energy loss with distance is the Bethe-Bloch equation.\cite{Leo94}

\[
\frac{dE}{dx} = 2\pi Na_r^2 m_e c^2 \rho Z Z^2 \left[ \ln \left( \frac{2m_e v^2 W_{\text{max}}}{I^2} \right) - 2\beta^2 \right]
\]  

(2.1)

- \( r_e \): classical electron radius \((2.82 \times 10^{-13}\text{ cm})\)
- \( m_e \): electron mass \((0.511 \text{ MeV})\)
- \( N_a \): Avogadro’s number \((6.022 \times 10^{23}\text{ mol}^{-1})\)
- \( I \): mean excitation potential
- \( Z \): atomic number of absorbing material
- \( A \): atomic weight of absorbing material
- \( \rho \): density of absorbing material
- \( z \): charge of incident particle in units of e
- \( \beta = v/c \) of incident particle
- \( \gamma = 1/\sqrt{1 - \beta^2} \)
- \( W_{\text{max}} \): maximum energy transfer in a single collision

For an incident particle of mass \( M \) the maximum energy transfer is

\[
W_{\text{max}} = \frac{2m_e c^2 \eta^2}{1 + 2s \sqrt{1 + \eta^2 + s^2}}
\]

(2.2)

where \( s = m_e/M \) and \( \eta = \beta \gamma \). For incident particles much larger than the electron mass \( W_{\text{max}} \approx 2m_e c^2 \eta^2 \).

The mean excitation potential is essentially the average orbital frequency \( \bar{\nu} \) from Bohr’s formula times Plank’s constant. Since oscillation strengths are not known for many materials the values usually come from fits to experimental data. Formulas for the mean excitation potential are\cite{Leo94},

\[
\frac{I}{Z} \approx 12 + \frac{7}{Z} \text{eV for } Z < 13
\]

(2.3)

\[
\frac{I}{Z} \approx 9.76 + 58.8Z^{-1.19} \text{eV for } Z \geq 13
\]

(2.4)

Using the Bethe-Bloch equation the energy loss of a proton traversing BC-505 is plotted in Figure 2.1 as a function of the proton’s beta value. The large energy loss experienced by low energy protons, \( \beta \leq 0.2c \), ensures that recoil protons from neutron collisions will be stopped quickly, \( \leq 1 \text{ cm} \), in the BC-505 scintillator.
2.2.2 Interactions of Electrons with Matter

Energy loss of electrons traversing matter stem from two processes, collisions, and Bremsstrahlung. Both processes are plotted in Figure 2.2 for hydrogen and carbon. These two factors are calculated separately from equations described below.

\[
\left( \frac{dE}{dx} \right)_{\text{Tot}} = \left( \frac{dE}{dx} \right)_{\text{coll}} + \left( \frac{dE}{dx} \right)_{\text{rad}}
\]

Energy loss from collisions

Energy loss from collisions can be calculated from a modified form of the Bethe-Bloch equation. This modification is needed due to the assumption that the incident particle is not deflected from its path during collisions made in the original formula. This was acceptable for a heavy charged
particle where $M \gg m_e$, however now $M = m_e$ and deflections will commonly occur. After modification the Bethe-Bloch equation becomes,[Leo94]

$$
-dE \frac{dx}{dx}_{\text{coll}} = 2\pi Na r_\text{e}^2 m_e c^2 \rho \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{\tau^2 (\tau + 2)}{2 (I/M_e c^2)^2} + F(\tau) \right].
$$

(2.5)

In the above equation $\tau$ is the particle kinetic energy in units of $m_e c^2$. The $F(\tau)$ function is defined as,

$$
F(\tau) = 1 - \beta^2 + \frac{\tau^2}{8} - \frac{(2\tau + 1) \ln 2}{(\tau + 1)^2} \quad \text{for } e^-
$$

(2.6)

$$
F(\tau) = 2 \ln 2 - \frac{\beta^2}{12} \left( 23 + \frac{14}{\tau + 2} + \frac{10}{(\tau + 2)^2} + \frac{4}{(\tau + 2)^3} \right) \quad \text{for } e^+
$$

(2.7)

All other variables have the same definition as in the previous section.

![Figure 2.2: Cross sections of the electron interactions for hydrogen and carbon [Gea94]. Energy (GeV) vs Cross section (Barns)](image)

26
Bremsstrahlung radiation

Bremsstrahlung radiation energy loss can be found from the following equation based on the Born approximation. [Leo94]

\[ -\left(\frac{dE}{dx}\right)_{\text{rad}} = NE_0\Phi_{\text{rad}} \]  \hspace{1cm} (2.8)

For \( m_e c^2 \ll E_0 \ll \alpha^{-1} m_e c^2 Z^{-1/3} \), \( \Phi_{\text{rad}} \) equals

\[ \Phi_{\text{rad}} = 4Z^2 r_c^2 \alpha \left( \ln \frac{2E_0}{m_e c^2} - \frac{1}{3} - f(Z) \right). \]  \hspace{1cm} (2.9)

For \( E_0 \gg \alpha^{-1} m_e c^2 Z^{-1/3} \), \( \Phi_{\text{rad}} \) equals

\[ \Phi_{\text{rad}} = 4Z^2 r_c^2 \alpha \left[ \ln \left( 183Z^{-1/3} \right) + \frac{1}{18} - f(Z) \right]. \]  \hspace{1cm} (2.10)

In the above formulae, \( E_0 \) is the initial total energy of the electron or positron, \( N \) is the number of atoms per cm\(^3\), and \( f(Z) \) is,

\[ f(Z) \approx a^2 \left[ (1 + a^2)^{-1} + 0.20206 - 0.0369a^2 + 0.0083a^4 - 0.002a^6 \right] \]  \hspace{1cm} (2.11)

where \( a = \alpha Z \). This is a correction to the Born approximation which takes into account the Coulomb interaction of the emitting electron in the electric field of the nucleus.

2.2.3 Interactions of Photons with Matter

Due to the absence of charge Coulomb interactions do not play a role in photon energy loss as in the previous sections. Photons have three well known interactions with matter and they are, photoelectric absorption, Compton scattering, and pair production. Figure 2.3 shows the three reactions together and their relative strengths for hydrogen and carbon. In the following sections all three photon processes will be discussed.
**Photoelectric effect**

The photoelectric effect involves an atomic electron absorbing a photon. The photon must have sufficient energy to overcome the electron’s atomic binding energy and thus turn the bound electron into a free electron. The energy of the outgoing electron will be \( E = h\nu - \phi \), where \( \nu \) is the incident photon frequency, and \( \phi \) is the binding energy. The photoelectric effect only applies to bound electrons as momentum conservation requires a nucleus to absorb recoil momentum.

The total cross section of the photoelectric effect for low energy photons, \( h\nu \ll m_e c^2 \) is,[Leo94]

\[
\sigma_{\text{photo}} = 4\alpha^2 \sqrt{2Z^3}\phi_0 (m_e c^2/h\nu)^{7/2}
\]

(2.12)

where \( \phi_0 = 8\pi r_e^2/3 = 6.651 \times 10^{-25} \text{ cm}^2 \). For higher photon energies Equation 2.12 is not valid as the shell structure of the atom must be accounted for. There will be a jump in the photoelectric spectrum as a result of electron shells becoming accessible or inaccessible in the region \( h\nu > m_e c^2 \).

**Compton Scattering**

Compton scattering is the process of photons scattering off free electrons. It should be noted that free electrons cannot absorb or emit photons. Figure 2.4 shows the scattering process. In this figure \( h\nu \) is the incident photon energy, \( h\nu' \) is the scattered photon energy, \( \theta \) is the scattered photon angle with respect to the incident photon’s direction, \( \varphi \) is the scattered electron’s angle with respect to the incident photon direction, and \( T \) is the scattered electron’s kinetic energy. The following formulae can be used to determine different quantities from a Compton scattering process. Using \( \gamma = h\nu/m_e c^2 \), we have

\[
h\nu' = \frac{h\nu}{1 + \gamma(1 - \cos \theta)}
\]

\[
T = h\nu - h\nu' = h\nu - \frac{\gamma(1 - \cos \theta)}{1 + \gamma(1 - \cos \theta)}
\]
The total cross section for Compton scattering is given by the Klein-Nishina formula below. [Leo94]

\[
\sigma_c = 2\pi r_e^2 \left( \frac{1+\gamma}{\gamma^2} \left[ \frac{2(1+\gamma)}{1+2\gamma} - \frac{1}{\gamma} \ln(1+2\gamma) \right] + \frac{1}{2\gamma} \ln(1+2\gamma) - \frac{1+3\gamma}{(1+2\gamma)^2} \right)
\]

(2.13)

Where \( r_e \) is the electron radius. A more relevant thing to know is the partial absorption cross section, \( \sigma_a \). Relating the absorption cross section to the total cross section above we have,

\[
\sigma_c = \sigma_s + \sigma_a
\]

where \( \sigma_c \) is the total Compton scattering cross section, \( \sigma_s \) is the partial scattering cross section, and \( \sigma_a \) is the partial absorption cross section. The usefulness of the absorption cross section
Figure 2.4: Compton scattering diagram.

is that it equals the average fraction of the total energy given to the electron during Compton scattering. Since electrons are easily captured by detection materials, the absorption cross section gives the amount of energy that would be detected. The remainder of the energy not imparted to the electron remains in the scattered photon. The scattered partial cross section gives the average energy remaining with the scattered photon. The formula for the scattered total cross section is,[Leo94]

\[
\sigma_s = \pi r_e^2 \left[ \frac{1}{\gamma^3} \ln(1 + 2\gamma) + \frac{2(1 + \gamma)(2\gamma^2 - 2\gamma - 1)}{\gamma^2(1 + 2\gamma)^2} + \frac{8\gamma^2}{3(1 + 2\gamma)^3} \right]. \tag{2.14}
\]

Using the formula for the scattered cross section above the absorption cross section may be found from \(\sigma_a = \sigma_c - \sigma_s\).

**Pair Production**

Pair production is the process where a photon is converted into a electron-positron pair. As with the photoelectric effect pair production requires the presence of a third body to conserve momentum. Usually in pair production it is a nucleus that absorbs the recoil momentum however it is possible for an atomic electron to act as the third body as well. The atomic electrons are also important in pair production due to their screening of the nucleus as with bremsstrahlung. Thus the pair production cross section is dependent on the parameter \(\xi\) which is small, \(\xi \simeq 0\), for complete
screening and large, $\xi \gg 1$, for no screening.\[Leo94\]

$$\xi = \frac{100mc^2\hbar}{E_+E_-Z^{1/3}}$$

In the above equation $E_+$ is the total energy of the outgoing positron, $E_-$ is the total energy of the outgoing electron, and $\hbar$ is the initial energy of the photon. The pair production cross sections for no screening and complete screening are given below.\[Leo 94\]

\[
\begin{align*}
\frac{d\sigma}{dE_+} &\approx 4Z(Z+1)\alpha^2\frac{E_+^2 + E_-^2 + 2E_+E_-/3}{(\hbar)^3} \left[ \ln \frac{2E_+E_-}{\hbar c^2} - \frac{1}{2} - f(Z) \right] \quad \text{for } \xi \gg 1 \quad (2.15) \\
\frac{d\sigma}{dE_+} &\approx 4Z(Z+1)\alpha^2\frac{dE_+}{(\hbar)^3} \left[ \left( E_+^2 + E_-^2 + \frac{2E_+E_-}{3} \right) \left( \ln(183Z^{-1/3}) - f(Z) \right) - \frac{E_+E_-}{9} \right] \quad \text{for } \xi \to 0 \quad (2.16)
\end{align*}
\]

where $f(Z)$ is Equation 2.11. The formulae above are from a Born approximation and thus are not valid for low energy or high $Z$ number.

### 2.2.4 Interactions of Neutrons with Matter

Neutron radiation like x-ray and $\gamma$ radiation is very penetrating since the Coulomb interaction is not involved. The primary neutron interaction is through the strong nucleon-nucleon force which has an interaction distance of the order $\simeq 10^{-15}$ m. Another possibility is for the neutron to undergo a weak interaction. The probability of a weak interaction is much less than a strong interaction as the weak interaction distance is of the order $\simeq 10^{-18}$ m.

If a neutron does interact via the strong nuclear force a variety of processes may occur. Restricting the discussion here to neutron energies below 100 MeV the possible reactions are listed below.\[Leo94\]

1. Elastic scattering with nuclei. This process is the principal mechanism of energy loss for neutrons in the MeV energy range. Elastic collisions are of the form $A(n,n)A$. 

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Figure 2.5: Cross section of neutrons through hydrogen and carbon \([Nnd02]\).

(II) Inelastic scattering with nuclei. This mechanism can only occur if the neutron has sufficient energy to excite the nucleus. Inelastic collisions are of the form \(A(n,n')A^+\), \(A(n,2n')B\), \(A(n,n'p)B\), etc.

(III) Neutron Capture by nuclei. The cross section for this mechanism depends on velocity and goes as \(\approx 1/\nu\). For different nuclei there are resonance peaks superimposed on the \(1/\nu\) dependence at varying energies. Neutron captures are of the form \(n + (Z,A) \rightarrow \gamma + (Z,A + 1)\).

(IV) Nuclear Fission. This mechanism is most likely to occur at low neutron energies in the eV to keV neutron energy range. Fissions are of the form \((n,f)\).

(V) Other nuclear reactions where charged particles are emitted from the absorbing nucleus. As with neutron capture the cross section for these processes goes with \(1/\nu\). These reactions are most noticeable at lower energies, eV to keV. Reactions in this category have the form \((n,p), (n,d), (n,t), (n,\alpha), (n,p\alpha)\), etc.
From the cross sections plotted in Figure 2.5 it is apparent that hydrogen dominants the interactions with neutrons in BC-505 scintillator cells for neutron energies below 1 MeV.

2.2.5 Summary

This concludes the review of the interaction of radiation with matter. Important topics for the understanding of the gain monitoring system operation were, recoil protons from the inelastic collision of neutrons with hydrogen, and the deposition of energy in materials by charged and charge neutral radiation.

2.3 P-N Junctions

The gain monitoring system requires a small yet brilliant light source with stable intensity and fast response time similar to the nanosecond scale neutron scintillation light emission from BC-505. These properties may be obtained with p-n junctions and their properties will be examined in the following discussion.

The most common p-n junction used is a single crystal structure where the two sides of the crystal are independently doped with different materials. For the p side of the junction an acceptor material is used to dope the crystal. This creates an excess of positive charge carriers, holes, on the p side. For the n side of the crystal the doping material is a donor. This creates an excess of negative charge carriers, electrons, on the n part of the crystal. The interface overlap between the p and n regions of the crystal need not be large for a flow of charge across the junction to occur when a potential is applied. The interface may be less than $10^{-4}$ cm thick.
2.3.1 Charge Equilibrium

Even though the electron and the hole rich sides of the junction will want to combine due to Coulomb attraction to form one neutral area, an equal and opposite Coulomb force resists the recombination. On the p side of the junction the impurity doping material are negatively ionized acceptor atoms. These negative charges are attracted to the positive holes on the p side. Since the number of holes and negative ions are equal, any diffusion of holes across the junction would lead to a local charge imbalance. Thus any significant diffusion is stopped by the Coulomb forces of the negative ions and the holes on the p side. On the n side the situation is similar with an equal number of free electrons and positively ionized donor atoms. Once again significant diffusion, this time of free electrons, does not occur because it would cause a local charge imbalance. Realistically a small amount of charge is able to cross the barrier leaving an excess of negative ions on the p side and positive ions and the n side. The charge imbalance creates an electric field across the junction that inhibits any further diffusion as the charges would have to move up the electric potential barrier to get to the other side. This potential difference keeps the remainder of the charges separated and the p-n junction intact.

The charge diffusion equilibrium across the p-n junction is temperature sensitive. Higher temperature particles will have more kinetic energy and thus will be able to climb a higher electric potential to get to the other side. When the junction settles into a thermal equilibrium the chemical potential of charge carriers of each type is constant for the entire crystal. The holes will satisfy the equation,[Kit96]

\[ k_B T \ln [p(r)] + e \phi(r) = \text{constant} \quad (2.17) \]

where \( \phi(r) \) is the electrostatic potential, and \( p(r) \) is the hole concentration. Electrons satisfy the equation,

\[ k_B T \ln [n(r)] - e \phi(r) = \text{constant} \quad (2.18) \]
where $n(r)$ is the electron concentration. From the equations it can be seen that $p$ will be high where $\phi$ is low, and $n$ will be low where $\phi$ is low. Or in other words, the magnitudes of $p$ and $\phi$ vary oppositely whereas the magnitudes of $n$ and $\phi$ vary concurrently.

In the crystal the total chemical potential is constant. The concentration gradient exactly cancels the electrostatic potential, so the net flow of each charge carrier type is zero. In equilibrium the recombination current, electrons rejoining with holes, $J_{nr}$ exactly cancels the creation current, neutral electron-hole pair splitting, $J_{ng}$ so that there is no net charge build up on either side of the junction. Mathematically $J_{nr} + J_{ng} = 0$ expresses this equilibrium.

![Depletion Region](image)

**Figure 2.6: A P-N junction at equilibrium.**

### 2.3.2 LEDs and Photodiodes

LEDs and photodiodes are both $p$-$n$ junctions, the intrinsic difference between them is the way in which the voltage is applied. For a LED the voltage is forward biased, and photodiodes have a reversed biased voltage. Reversed biased means that a positive bias is applied to the $n$ side of the junction, and negative bias on the $p$ side. In a LED electrons can overcome the electric potential inhibiting them from crossing the junction if sufficient voltage is applied. Conduction
band electrons then will recombine with valence band holes releasing photons. The size of the band gap will determine what wavelength photon is produced during the recombination of the electron and hole pair. The larger the band gap the shorter the wavelength of photon is produced. With photodiodes an incident photon, if energetic enough, will create an electron-hole pair. The electron and the hole are swept through the junction in opposite directions, thus creating a current in the photodiode.

2.3.3 Summary

In conclusion a P-N junction in the form of a light emitting diode is a reliable light source. LEDs are more compact than incandescent light emitters, provide a more stable light intensity, and age slowly compared to the conventional incandescent light bulb. A further benefit of LEDs is the ability to pulse the LED very rapidly down to nanosecond scales and the light intensity produced is linearly proportional to the driving voltage. All of the characteristic mentioned here are necessary or beneficial for the operation of the proposed gain monitoring system.

2.4 Fiber Optics

Several processes determine the light collection ability of a fiber optic cable as well as the light transmission efficiency. In the following sections the interactions and physical properties of fiber optic cables will be discussed. The goal for the gain monitoring system is to determine what fiber optic cable would provide both large light collection and efficient light transmission.

2.4.1 Reflection of Light

When light comes to an interface between two media with differing refractive indices some light will be reflected. The exact amount of the incident light reflected will depend on the angle of incidence, $\Theta_i$. The reflected ray will be in the same plane as the incident wave, it will be on the
opposite side of the surface normal vector than the incident ray, and the angle between the reflected ray and the normal will be $\Theta_r$ where $\Theta_i = \Theta_r$ (See Figure 2.7).

![Figure 2.7: Reflection of light.](image)

### 2.4.2 Refraction of light

When a light ray enters an optically denser material from an optically less dense material the light ray will be bent toward a refraction angle of $\beta$. If the refractive indices of the first and second media are, $n_1$ and $n_2$ respectively, and the speed of light in the first and second media are $v_1 = \frac{c_0}{n_1}$ and $v_2 = \frac{c_0}{n_2}$, where $c_0$ is the speed of light in a vacuum. Then for an isotropic material Snell’s law applies.

\[
\frac{\sin \alpha}{\sin \beta} = \frac{v_1}{v_2} = \frac{n_2}{n_1},
\]

where $\alpha$ is the angle of the incident light ray to the normal vector, and $\beta$ is the angle of the refracted light ray to the normal vector (See Figure 2.8).

### 2.4.3 Total Internal Reflection

When a light ray meets a contact point leaving a more optically dense material to a lesser optically dense material there is a certain angle of incidence $\alpha_0$ for which the angle of refraction becomes
equal to 90° so that the refracted light ray travels parallel to the boundary. The angle $\alpha_0$ is called the critical angle of the two media. To calculate the critical angle the formula, $\sin\alpha_0 = \frac{n_2}{n_1}$, may be used. For angles greater than $\alpha_0$ the light ray would have a refracted angle greater than 90°, $\beta > 90°$. This cannot be so the ray remains in the denser medium and is totally internally reflected.
2.4.4 Numerical Aperture

The process of total internal reflection can be used to determine the angular light gathering ability of a fiber optic cable. This angular light gathering ability of a fiber is defined by the numerical aperture. In optical waveguides total internal reflection is used to transmit the light down the fiber. For fibers with two refractive indexs, the core with \( n_1 \), and the cladding with \( n_2 \) where \( n_1 > n_2 \), the incident ray must have an angle \( \Theta \) such that the refracted angle is less than or equal to \( 90^\circ - \alpha_0 \).

Figure 2.10 shows the light ray path for an angle \( \Theta \). If a light ray enters the waveguide with a angle \( \Theta > \Theta_{\text{max}} \) then at the core-cladding interface it will have an angle less than \( \alpha_0 \) and thus will not be internally reflected, but will be refracted into the cladding material and removed from the remainder of the transmitted light.

\[
\sin \Theta_{\text{max}} = \frac{n_1}{n_0} \Rightarrow \sin \Theta_{\text{max}} = \sqrt{n_1^2 - n_2^2}, \tag{2.20}
\]

where \( n_0 = 1 \) the refractive index of air. The greatest possible entry angle \( \Theta_{\text{max}} \) is called the acceptance angle of the fiber. The angle \( \Theta_{\text{max}} \) is dependent on two variables, \( n_1 \) and \( n_2 \). The sine of the acceptance angle is called the Numerical Aperture \( \equiv \text{NA} \equiv \sin \Theta_{\text{max}} \) which defines the angular acceptance and hence angular light gathering ability of the optical fiber.

Figure 2.10: Example of a wave guide.
2.4.5 Index Profiles of Fiber Optic Cables

In the last example the numerical aperture of a fiber optic cable is calculated the index of refraction profile considered was of a step index fiber. There are a wide range of graded index profiles in addition to the step index profile and each one effects the properties of the fiber optic cable. The important feature of graded index fibers is that they are able to reduce the temporal dispersion of light pulses as they travel through a fiber optic cable. The index profiles are functions of radius and are described by the formula [Mah01]

\[
n^2(r) = n_1^2 \left[ 1 - 2 \cdot \Delta \cdot \left( \frac{r}{a} \right)^g \right] : \text{for } r < a
\]

\[
n^2(r) = n_2^2 = \text{constant} : \text{for } r \geq a
\]

where,

- \(n_1\) is the index of refraction along the fiber axis
- \(\Delta\) is the normalized refractive index difference
- \(r\) is the distance from the axis of the fiber in \(\mu\text{m}\)
- \(a\) is the core radius in \(\mu\text{m}\)
- \(g\) is the profile exponent
- \(n_2\) is the index of refraction of the cladding

The normalized refractive index difference is related to the numerical aperture of the fiber and is defined by

\[
\Delta = \frac{NA^2}{2 \cdot n_1^2} = \frac{n_1^2 - n_2^2}{2 \cdot n_1^2}.
\]

Only for \(g \to \infty\) does the refractive index remain constant in the core of the fiber. Figure 2.11 shows a few types of core index profiles.
2.4.6 Single Mode and Multi Mode Fibers

An important quantity for the description of an optical fiber is the V number. The V number is dependent on three variables, the core radius $a$, the numerical aperture $\sin \Theta_{\text{max}}$, and the wavelength of the light used $\lambda$. The V number is a dimensionless parameter and is given by [Mah01]

$$V = 2\pi \cdot \frac{a}{\lambda} \cdot \sin \Theta_{\text{max}} = k \cdot a \cdot \sin \Theta_{\text{max}}. \quad (2.23)$$

The number of modes, which are solutions to the wave equation for different eigenvalues, that are guided in the core of the fiber is denoted by $N$. The value of $N$ is dependent on the V number and the $g$ profile exponent number. The $N$ number is approximately

$$N \approx \frac{V^2}{2} \cdot \frac{g}{g+2}. \quad (2.24)$$

For a step index profile ($g \to \infty$) the number of modes is approximately $N \approx \frac{V^2}{2}$. If the V number in an optical fiber with a step index profile becomes smaller than a critical value $V_c = 2.405$, then only the fundamental mode $L_{01}$ can propagate down the fiber. An optical fiber with only one propagating mode is called a single mode fiber. All other fibers with more than one propagating mode are called multi mode fibers.
To understand the origins of the critical $V$ number $V_c = 2.405$ one must consider the solutions to a cylindrical waveguide. To find solutions for the interior of a cylinder with radius $a$ and length $l$ the singular Poisson equation $\nabla^2 \Phi = -\delta(r - r')$ must be solved, where $\Phi$ is the potential of the electromagnetic field. The equation for $\Phi$ will be solved by seeking a solution using a Green’s function in cylindrical coordinates.

$$\nabla^2 G = \left( \frac{1}{\rho^2} \frac{\partial}{\partial \rho} \left( \rho^2 \frac{\partial}{\partial \rho} \right) + \frac{1}{\rho^2} \frac{\partial^2}{\partial \phi^2} + \frac{\partial^2}{\partial z^2} \right) G = -\frac{\delta(\rho - \rho')}{\rho} \delta(\phi - \phi') \delta(z - z') \quad (2.25)$$

The boundary conditions are $G = 0$ for $\rho = a$, $z = 0$ and $z = l$. Due to cylindrical symmetry the Green’s function should be periodic with respect to $\phi$. The Green’s function should also be invariant under the exchange of $\phi \rightarrow -\phi$ due to the symmetry. Hence the $\phi$ dependence can be assumed to be $\cos(m\phi)$, where $m$ is an integer.

The three variables are separable so the Green’s function will be of the form,

$$G(\mathbf{r}) = \sum_m R_m(\rho) Z_m(z) \cos(m\phi). \quad (2.26)$$

Substituting the Green’s function in equation 2.26 into Poisson’s equation and separating out the
different parts of the equations gives,

\[
\left( \frac{d^2}{dp^2} + \frac{1}{\rho} \frac{d}{dp} - \frac{m^2}{\rho^2} + k^2 \right) R_m(\rho) = 0, \tag{2.27}
\]

\[
\left( \frac{d^2}{dz^2} - k^2 \right) Z_m(z) = 0, \tag{2.28}
\]

where \(k^2\) is a constant. To determine the modes of light that will propagate down the waveguide the radial and azimuthal eigenvalues must be known. The azimuthal eigenvalues are given from the solution to \(\phi\) above, \(m = 0, 1, 2, \ldots\). The radial eigenvalues are found from solving the differential equation with respect to \(\rho\) listed above. Solving Equation 2.27 gives the \(m\)-th order Bessel functions,

\[
R_{mn}(\rho) = A J_m \left( \frac{x_{mn}\rho}{a} \right) + B Y_m \left( \frac{x_{mn}\rho}{a} \right) \tag{2.29}
\]

The Bessel functions of the second kind diverge at \(R_m(\rho = 0)\) hence \(B\) must equal zero. The final solution for the radial function is then,

\[
R_{mn}(\rho) = A J_m \left( \frac{x_{mn}\rho}{a} \right) \tag{2.30}
\]

where \(A\) is a constant to be determined from boundary conditions, and \(x_{mn}\) are the radial eigenvalues corresponding to the \(n\)-th root of the \(m\)-th Bessel function. The unique wave numbers of modes that can propagate in the wave guide are given by \(k_{mn} = \frac{x_{mn}}{a}\) as long as the radial eigenvalue is less than the core radius of the waveguide. For incident light of frequency \(\omega\) the cut off frequencies are given by, [Gri99]

\[
\omega_{mn}^c = \frac{c x_{mn}}{a}
\]

allowed wave numbers can be written in terms of the cutoff frequency :

\[
k = \frac{1}{c} \sqrt{\omega^2 - \omega_{mn}^2} = \sqrt{\left( \frac{2\pi}{\lambda} \right)^2 - \left( \frac{x_{mn}}{a} \right)^2}
\]

It is apparent from the wave number formula that if \(\omega_{mn} > \omega\) then the resulting frequency would be imaginary and no wave propagation would occur, only exponential damping of the wave. Returning
now to the value of \( V_c \) we see that \( V_c = x_{01} = 2.405 \). Hence for a fiber to be multi mode it must have a \( V \) number greater than the first zero value of the \( J_0(x) \) Bessel function.

In summary the importance of the \( V \) number is that there are characteristic differences between single mode and multi mode fibers. Single mode fibers are thin cored and only transport the fundamental mode of light down the fiber. All higher modes in a single mode fiber propagate at a radial distance that is larger than the core radius. This would put the higher modes in the cladding of the fiber optic cable and are quickly lost. The benefit of multi mode fibers is that these higher modes are not lost and more light is transported down the fiber for system use. A further advantage of multi mode fibers is larger tolerances for error when making a connection between two fibers. If a 500 \( \mu \)m core fiber is shifted by 50 \( \mu \)m during coupling (See Figure 2.14) there is a small loss of light. However single mode fiber core may only be 50 \( \mu \)m wide and such a misalignment would stop any light from being transmitted. The disadvantage of multi mode fibers is that graded index profiles are needed to stop temporal dispersion of the light traversing the fiber. The use of graded index profile fibers is in general more expensive than step index fibers so that the benefits must be weighed against the costs when choosing a fiber.

2.4.7 Transmission Attenuation by Fiber Optic Cables

All fiber optic cables attenuate the signals that propagate through them. The equation governing the loss of light power while traversing a fiber optic cable is

\[
\text{dB} = 10 \log_{10} \frac{P(L)}{P(0)} \quad [\text{Mah01}]
\]

Where \( P(0) \) is the initial signal power at the beginning of the cable, \( P(L) \) is the signal power at a distance \( L \) down the cable, and dB is the signal loss in decibels. For more convenient use this formula may be written as

\[
\alpha L = 10 \log_{10} \frac{P(L)}{P(0)}
\]

Where \( \alpha \) is the transmission loss coefficient of the cable in \( \frac{\text{dB}}{\text{m}} \), and \( L \) the distance down the cable in meters. Due to the fact that the transmission loss coefficient is negative \( \alpha \) can be replaced with \( -\alpha \), where \( \alpha \) is the magnitude of \( \alpha \). The power loss equation
then becomes

\[-\alpha L = 10 \log_{10} \frac{P(L)}{P(0)} \implies \alpha L = 10 \log_{10} \frac{P(0)}{P(L)}.\] (2.32)

### 2.4.8 Fiber Optic Connectors

The method of determining the quality of a fiber optic connection is to measure the insertion loss on the system. Insertion loss is defined as the attenuation of a signal due to the insertion of a connector. There are three main causes of insertion loss: axial offsets, fiber separation, and angular misalignment.

Figure 2.13 gives an example of angular misalignment. As \( \phi \) increases the attenuation loss of signal becomes larger. For \( \phi > \Phi_{\text{max}} \) no transmitted signal would propagate through the connector at all. Angular misalignments can occur from connector defects which cause a bend in the joint axis.

![Figure 2.13: An example of fiber angular misalignment.](image)

In Figure 2.14 an axial offset that would result in signal attenuation is demonstrated. \( \delta \) is a measure of the misalignment. A larger misalignment of the fibers results in more signal loss. At \( \delta = D \) there will be no transmitted signal through the fiber connection. Axial offsets may occur due to manufacturing defects in either the fiber optic cable, or the connection adapter. Many fiber optic
cables are commonly made with an exterior sheath for protection. Attenuation problems arise when the core is not centered in the sheath. All industrially made fibers will suffer from this problem to varying degrees as it is impossible to manufacture a cable with the core perfectly centered. Similarly the connectors can suffer from manufacturing imperfections leading to an axial offset.

![Figure 2.14: An example of fiber axial offset.](image1)

![Figure 2.15: An example of fiber end face separation.](image2)

Lastly, Figure 2.15 gives an example of fiber separation resulting in signal attenuation. The further apart fibers are from the joint the more attenuation will occur. Fiber separation would occur if the connector pieces do not join properly or if the fiber was not flush with the end of the connector.

### 2.4.9 Summary

This concludes the review of fiber optic cables. Several important characteristics of fiber optic cables must be considered when a fiber is chosen for the gain monitoring system. The first is that the numerical aperture $\sin \Theta_{\text{max}}$ determines the light gathering ability of the fiber and should be as large as possible. Second the number of light modes that can traverse the fiber is determined by the $V$ number and is related to the core diameter of the fiber, the wavelength of light incident of the fiber, and the numerical aperture. A large $V$ number would be optimal for increased light
transfer through the fiber. Similarly to maximize the amount of light transferred the fiber optic
cable should be chosen so that the transmission loss coefficient of the fiber is as small as possible
for the wavelength of light being used. A last consideration is the type of index profile that the
fiber should have which will determine the temporal dispersion of the fiber for multi mode optical
cables.

2.5 Pulse Shape Discrimination (PSD)

Fast PMTs working on a $\simeq 10^{-9}$ s scale allow the use of a technique called pulse shape
discrimination (PSD). PSD allows particles to be distinguished from the PM output pulse shape,
particularly from the fall time of the pulse. It is valuable during an experiment to be able to identify
relevant events so they can be recorded. It is also valuable to be able to disregard irrelevant events
thus freeing up processing time and other resources. For the Blowfish neutron detector array it
is important to be able to distinguish between valuable data, like neutron detection, and other
unimportant events like electron and photon detection. To understand how PSD works one must
first understand how a scintillator emits light. When the kinetic energy of incident particles is
absorbed by the scintillator, atomic electrons are put into excited states or become free electrons.
The subsequent deexcitations of these atoms produces the scintillation light which is guided to the
PMT for amplification. Figure 2.16 [Kno00] shows typical levels of electron excitation for singlet
and triplet states.

The deexcitation of electrons to the ground state is governed by exponential decay. Excited states
have a lifetime $\tau$, which governs the decay of the state. The intensity of light emitted from the
material following excitation would then be,

$$I = I_0 e^{-t/\tau}$$
Due to the fact that many excitation levels are available for electrons to populate and that these levels will have varying lifetimes the equation for scintillation light emission becomes a sum over the occupied excited states.

\[ I = I_i \sum_{i=1}^{n} e^{-t_i} \]  \hspace{1cm} (2.33)

This sum over excited states is what makes PSD possible. The scintillation material will have a different stopping power, \( \frac{dE}{dx} \), depending upon the particle traversing it. Particles that deposit a small amount of energy traversing a length \( dx \) will primarily excite atomic electrons to singlet states with a short lifetime. Heavy charged particles like the proton will deposit a larger amount of energy traversing the length \( dx \) thereby exciting a larger portion of the atomic electrons to triplet states which have longer lifetimes than singlet states. Thus there would be a corresponding shift in the emitted scintillation light intensity pattern with more light emitted later in time. This shift of light intensity in time will effect the output of the PMT which is dependent on light input.

Figure 2.16: Jablonski diagram of typical molecular electron excitation levels [Kno00].
2.5.1 Photomultiplier Circuit

The anode current of a PMT will depend on the scintillator decay lifetime, $\tau_s$, and may be written,[Leo94]

$$I(t) = \frac{GNe}{\tau_s} \exp\left( -\frac{t}{\tau_s} \right)$$ (2.34)

where $G$ is the gain of the PM, $N$ is the number of photoelectrons, and $e$ is the charge of the electron. If the PM is modeled as a current generator with intrinsic resistance and capacitance from components like the anode and PM cables, Figure 2.17 gives the equivalent circuit.

![Equivalent circuit for a photomultiplier tube.](image)

From the circuit diagram in Figure 2.17 an equation for current can be written in the form,

$$I(t) = \frac{V(t)}{R} + C \frac{dV(t)}{dt}.$$ (2.35)

Solving this first order differential equation gives

$$V(t) = -\frac{GNeR}{RC - \tau_s} \exp\left( -\frac{t}{RC} - \frac{t(\tau_s - RC)}{\tau_s RC} \right) + A \exp\left( -\frac{t}{RC} \right)$$ (2.36)
Using the initial condition $V(t = 0) = 0$ determines that $A = \frac{GNeR}{RC - \tau_s}$. Using this value for $A$ and $RC = \tau$, the voltage equation becomes,

$$V(t) = -\frac{GNeR}{\tau - \tau_s} \left[ \exp \left( -\frac{t}{\tau_s} \right) - \exp \left( -\frac{t}{\tau} \right) \right], \quad \tau \neq \tau_s \quad (2.37)$$

$$V(t) = \left( \frac{GNeR}{\tau_s^2} \right) t \exp \left( -\frac{t}{\tau_s} \right), \quad \tau = \tau_s \quad (2.38)$$

From Equations 2.37 and 2.38 it is apparent that the scintillator lifetime $\tau_s$ will determine anode voltage characteristics including rise and fall times. These changes in pulse shape can be used to differentiate between particle types. The output is measured to find how much of the pulse area is contained in the leading edge of the pulse and how much area is in the tail end of the pulse. If neutrons are the desired particle to be detected then the recoil proton from neutron events will have a longer pulse decay time than photons and electrons giving them pulse tails with more area. Thus integrating charge over two different regions of the pulse, first half and second half for example, and taking the ratio will give approximately the same number for like particles. This processes may be carried out using analog circuitry or digital techniques. A measure of how well the PSD process can discriminate between different particles is given by the merit value $M$, $M \equiv \frac{X}{W_a + W_b}$, where $X$ is the separation of the particle ratio peaks, and $W_a, W_b$ are the particle a and b FWHM respectively. (See Figure 2.18).

### 2.5.2 Summary

The technique of pulse shape discrimination allows the sorting of particle types by analyzing the output signal from a PMT. PSD is possible because different particles excite atomic electrons in a unique distribution. The scintillation light emitted by the atomic electrons when they return to the ground state creates a unique pulse shape that is amplified by the PMT and measured electronically. As with all techniques PSD has limitations. For accurate particle classification the particle grouping shown in Figure 2.18 must be separated enough so that the different groups
are distinguishable. Otherwise mixing of particle types will occur when the particle groups begin overlapping.
Chapter 3

Development

3.1 Apparatus Criterion

The gain monitoring system has four major components, a light source, the trigger pulser, LED monitors, and fiber bundles. Each of these components must be selected to maximize the overall efficiency of the system while minimizing instability and noise. To guide this process what is known from theory is applied to choose the best components.

3.2 Light Source

The light source needed for the gain monitoring system must be capable of fast pulsing, on the order of nanoseconds, and have consistent luminescence for constant voltage. The color of the light source must also be in the blue spectral range to coincide with the color of scintillation light from BC-505 detector cells. Finally the light source must be small in size and light weight so that it can be mounted on the array easily.
Table 3.1: Common types of LEDs.

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Wavelength (nm)</th>
<th>Band Gap (eV)</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaP</td>
<td>520</td>
<td>2.4</td>
<td>green</td>
</tr>
<tr>
<td>SiC</td>
<td>480</td>
<td>2.6</td>
<td>blue</td>
</tr>
<tr>
<td>GaAsP</td>
<td>720</td>
<td>1.7</td>
<td>red</td>
</tr>
</tbody>
</table>

All of these characteristics are achievable using a LED, as discussed in section 3. The materials for the P and N sides of the junctions may be chosen so that photons produced by electron-hole recombination are blue. Table 3.1 lists some commonly used LED materials. Due to the fact that emitted photons from LEDs are from electron-hole recombination, short light pulsing is possible to the order of the electron-hole excited state life time. The minimum LED pulse time must be under the 30 ns maximum set by the pulse time for neutron detection. Fast LEDs are the light sources chosen for the gain monitoring system as they meet all the necessary requirements. For the gain monitor design with a thin fiber optic bundle forward focusing LEDs would be advantageous.

3.2.1 NSPB Series Light Emitting Diode

The Nichia Corporation produces several models of blue LEDs which have fast response times. The NSPB model of blue LEDs come in several sizes and with different directivity angles. Directivity is defined as the angle from the central axis at which the $\Theta = 0^\circ$ intensity has decreased by $\frac{1}{2}$ (See Figure 3.1).

For preliminary testing three types of blue LED were ordered, the NSPB300A, NSPB310A, and the NSPB320BS. Table 3.2 compares the different models of LEDs. Figure 3.2 shows the NSPB310A
model LED. All of the LEDs are about the same size, 4 mm wide and 30 mm long. The peak emission wavelengths of all three LEDs are centered at 465 nm.

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Directivity #</th>
<th>Luminous Intensity (candela)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>15</td>
<td>2.30</td>
</tr>
<tr>
<td>310</td>
<td>30</td>
<td>1.16</td>
</tr>
<tr>
<td>320</td>
<td>45</td>
<td>0.70</td>
</tr>
</tbody>
</table>

### 3.2.2 NSPB Series Testing

To determine which of the NSPB series LEDs would be most suitable for the gain monitoring system the light intensity profile of each LED was measured. The light intensity measurement was taken by illuminating a sheet of paper while applying a constant voltage to the LED. A CCD camera on the opposite side of the paper acquired a picture of the light pattern. An exposure time of a few seconds was used. This processes was applied because the LED is too bright for a direct exposure by the CCD camera. If the CCD camera was directly exposed to the LED the pixels on the CCD camera would overflow for all standard operating voltages of the LED. Thus the piece
of paper between the camera and the LED acts as a filter reducing the amount of light reaching the camera. The recorded light intensity pattern from the CCD camera was plotted using Physics Analysis Workstation (PAW) software for each LED. Figures 3.3 and 3.4 are PAW surface plots of LED intensity captured by the CCD camera for each NSPB model.

The LED model number deemed best for the gain monitor was the NSPB310 series. The brightest LED, the NSPB300, was not usable due to the structured pattern of light emission. The NSPB300 has high intensity peaks at an emission angle of $\theta = 0^\circ$ followed by a dark area which is then surrounded by a ring of light (See Figure 3.3). The remaining two LED models NSPB310 and NSPB320 gave usable light patterns (See Figure 3.4). The NSPB320 intensity profile was broader than the NSPB310 and not as intense. For this reason the NSPB320 LED was rejected so that higher illumination levels would be available. The NSPB310 does have a prominent peak structure which is not ideal for illuminating the fiber optic bundle. The ideal pattern would be a step function that has uniform intensity across the width of emission angles. However the peak pattern of the NSPB310 is usable if the LED is placed a few centimeters away from the bundle so that the intensity change from fiber to fiber is small.

After the selection process the NSPB310 was tested further to determine if the LED light intensity increased linearly with pulser driving voltage. A linear relation would be beneficial for easy adjustment of LED light output during experiments by altering the LED driving voltage. An example of such a situation is a beam energy change. If the incident $\gamma$-ray energy on the target is raised or lowered then the kinetic energy of the photodisintegration products would change as well. To keep the detection peaks within the ADC scale a gain change is required. The change in gain would then cause the LED peak to shift ADC channel location. Returning the LED peak to a convenient location on the ADC histogram plot would require the intensity of the LED to be altered by adjusting the driving voltage coming from the pulser. Figure 3.5 shows LED intensity
and pulser voltage are linear. Had the relation not been linear the LED could still be used as a nonlinear relation between light intensity and pulser voltage could still be fine tuned, but with more difficulty. At the same time linearity was tested the pulse to pulse stability of the LED was measured. The formula used to calculate the stability was

\[
\text{Resolution} \equiv \frac{\text{FWHM}}{\text{ADC}_{\text{mean bin value}} - \text{ADC}_{\text{pedestal}}} \times 100\%.
\]
Three different pulse widths were chosen and tested in separate trials. The pulse widths tested were, 10 ns, 20 ns, and 30 ns. The pulse width of 10 ns was chosen because it was the limit of the BNC 555 pulser capability. Pulse widths longer than 30 ns were not investigated as the resulting pulses would be too long to fit easily into the electronic gate times for neutron detection. The results for the resolutions tests are plotted in Figure 3.7. The graphs show that LED resolution is better for longer pulse widths. To achieve a balance between resolution and short pulses for gate timing the 20 ns pulse width setting was chosen for the remainder of testing and future operation.

Lastly the PMT high voltage dependence was tested during constant pulser voltage conditions to verify that the mean ADC value increased linearly with PMT high voltage changes. This linearity relation was tested to confirm the operation specifications of the XP2262B PMT bases used during Blowfish experiments. Figure 3.6 shows that constant light illumination does increase linearly with PMT voltage.

Figure 3.5: Linear relationship between LED voltage and LED intensity confirmed.

Figure 3.6: Linearity test of the PMT voltage with constant LED intensity.
Figure 3.7: NSPB310 LED resolution for 10ns, 20ns, and 30ns pulse widths.

3.2.3 LED Housings

To prevent light contamination down the fiber optic bundles the LED is situated inside a enclosed light tight cavity. The bundle is connected to the LED housing using a mounting port which is secure from light contamination. The entire device would then be situated inside a mounting box with only one port for the bundle mount exposed. The mounting box is made out of aluminum and can easily attach to the Blowfish array using brackets. The aluminum box also serves as a secondary source of protection from light contamination. Figure 3.8 shows the prototype drawings for the LED housing and the fiber bundle mount.
The construction of the LED Housing components was done by the University of Saskatchewan Department of Physics and Engineering Physics Machine Shop. All of the housing components were made from solid aluminum and machined to size. Figure 3.9 shows the finished LED mount and the aluminum rod that is used for the fiber optic bundle. Six of the LED housings and boxes were made. Only four are needed to fulfill the requirements of the current array, however future expansions may necessitate two additional LED light sources.

Figure 3.8: Draft designs for the LED housing and fiber bundle mount.
3.3 Trigger Pulser

The light source trigger pulser for the gain monitoring system must meet several requirements to operate in concert with the current neutron detector array system. Most important is the ability of the pulser to produce narrow voltage signals capable of fitting within the TDC timing gates. To incorporate the pulser into the gate timing it must be able to generate square pulse widths of 30 ns or shorter. The second requirement is that the pulser output is adjustable with a range between 2 V and 4 V or better. This tunable voltage is needed to vary the LED light output using the pulser. Most blue LEDs do not produce light unless a minimum forward voltage of 2 V is applied, hence this is the minimum needed voltage setting. The final requirement is that the pulser has multiple channel outputs as more than one LED is necessary and a pulser monitor channel is needed.
3.3.1  BNC 555 Bench Top Pulser

The BNC 555 bench top pulser met or exceeded all the requirements needed. In the area of voltage output the pulser is capable of supplying 1 - 6 V into a 50 Ω load. All of the 8 channels of the BNC 555-8c model have independent voltage adjustment. The pulse widths and delays are also channel independent and can be set individually. The minimum pulse width of the BNC 555 is 10 ns, however the maximum pulse voltage of 6 V can not be achieved for pulse widths less than \( \approx 40 \) ns. Figure 3.10 shows a snapshot of the benchtop pulser. [Dun05]

Figure 3.10: The BNC 555 benchtop pulser.

3.3.2  BNC 555 Pulser Testing

Table 3.3 gives the performance of the BNC 555 pulser for a variety of pulse width settings. The important features that are recorded in the table are rise and fall times, and maximum voltage output. For the pulser tests the output channels of the BNC 555 were connected to charge integrating ADCs. Figure 3.11 shows data for pulser channels B and C, which were adjusted to different voltage settings. The first two plots show the raw ADC data collected from the two channels with respect to time. The last plot shows the ADC peak values from the two channels.
plotted against each other. If the pulser voltage drift is a constant factor of the manual setting then two channels plotted together should be linear as in Figure 3.11. Thus the pulser channels drift by the same fraction. If one channel is monitored then from the single monitored channel the changes in voltage of the other channels may be determined. The pulser drift tests demonstrate that room temperature changes result in variations in output voltage. The changes in voltage however are uniform across all eight pulser channels.

Table 3.3: BNC 555 performance for a variety of pulse width settings.

<table>
<thead>
<tr>
<th>Pulse Width Setting (ns)</th>
<th>Pulse FWHM (±0.1ns)</th>
<th>Rise Time (±0.1ns)</th>
<th>Fall Time (±0.1ns)</th>
<th>Maximum Voltage Output (±0.1V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>12.3</td>
<td>9.0</td>
<td>5.4</td>
<td>4.2</td>
</tr>
<tr>
<td>20</td>
<td>21.3</td>
<td>12.1</td>
<td>5.5</td>
<td>5.0</td>
</tr>
<tr>
<td>30</td>
<td>30.2</td>
<td>16.3</td>
<td>5.6</td>
<td>5.5</td>
</tr>
<tr>
<td>40</td>
<td>39.7</td>
<td>18.8</td>
<td>5.6</td>
<td>5.7</td>
</tr>
<tr>
<td>50</td>
<td>49.3</td>
<td>20.1</td>
<td>5.7</td>
<td>5.8</td>
</tr>
</tbody>
</table>

3.4 LED Monitor

The two candidates investigated for the LED monitor detector were photodiodes or a scintillator detector with PMT. The photodiodes were abandoned in favor of the scintillator detector due to the fact that the scintillator detector could be monitored for gain changes easily using a radioactive source.
3.4.1 Scintillator

For the scintillator detector to be effective it must be dense enough to stop $\gamma$-rays within the detector volume. If scattering occurs and $\gamma$-rays escape the detector volume then a photopeak will not form and only the Compton edge is observed. Because it is easier to accurately determine a peak position than a Compton edge location, a photopeak is more desirable. The energy of $\gamma$-rays used is in the range of 0.511 - 1.27 MeV. Table 3.4 lists some commonly used $\gamma$ sources.

Candidate materials for the scintillation detector are Cerium doped fast inorganic crystals. These crystals are several times more dense than water and have a relatively fast photon emission decay time compared to other well known crystals like Sodium Iodide (NaI). Some of the scintillation materials considered are listed in Table 3.5. [Kno00]
Table 3.4: Common radioactive $\gamma$-ray sources.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half-life (yr)</th>
<th>Photon Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}_{11}$Na</td>
<td>2.6</td>
<td>0.511, 1.27</td>
</tr>
<tr>
<td>$^{54}_{25}$Mn</td>
<td>0.855</td>
<td>0.835</td>
</tr>
<tr>
<td>$^{60}_{27}$Co</td>
<td>5.2</td>
<td>1.173, 1.333</td>
</tr>
<tr>
<td>$^{137}_{55}$Cs</td>
<td>30.2</td>
<td>0.662</td>
</tr>
</tbody>
</table>

Table 3.5: Common Cerium doped fast inorganic crystals [Sci05].

<table>
<thead>
<tr>
<th>Name</th>
<th>Specific Gravity</th>
<th>Max. Emission Wavelength (nm)</th>
<th>Decay Time ($\mu$s)</th>
<th>Photons/MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSO</td>
<td>6.71</td>
<td>440</td>
<td>0.056 (90%)</td>
<td>9000</td>
</tr>
<tr>
<td>LSO</td>
<td>7.4</td>
<td>420</td>
<td>0.047</td>
<td>25000</td>
</tr>
<tr>
<td>LuAP</td>
<td>8.4</td>
<td>365</td>
<td>0.017</td>
<td>17000</td>
</tr>
<tr>
<td>YAP</td>
<td>5.37</td>
<td>370</td>
<td>0.027</td>
<td>18000</td>
</tr>
</tbody>
</table>

The GSO (gadolinium-silicon-trioxide) crystal was chosen because it had a maximum emission wavelength similar to BC505 and is sufficiently dense to provide a full energy deposition peak from a $^{137}$Cs radioactive source. A second option LSO (lutetium-silicon-trioxide) was not chosen despite its preferable higher density because of its naturally occurring radioactivity. The isotope $^{176}_{71}$Lu makes up 2.6% of naturally occurring lutetium and is radioactive undergoing beta decay with a half life of $3.78 \times 10^{10}$ yr. For any LSO detector the activity would be $295.8 \frac{\text{decays}}{\text{s-cm}^3}$. With each $\beta$ decay there is a deexcitation photon cascade that releases 2 to 3 $\gamma$-rays. The Q-value of the decay is 1192.8 keV and results in an approximate average energy of 671.8 keV deposited.
in the detector depending on detector volume. For this reason LSO detectors will not be used as the radioactive energy deposition is in the range of values were possible radioactive source peaks would occur. The LSO detector is not useful as a self calibrating detector either, because the FWHM of the $\beta$-decay photopeak is broad due to the multiple branching channels and is equal to $\approx 200$ keV determined by Geant simulations. Geant is a software simulation package for the interaction of particles and materials. [Gea94] The other two candidates LuAP and YAP were not chosen because the maximum emission wavelength was not in the blue area of the spectrum.

### 3.4.2 Detector Size Determination

Calculations and simulations determined the minimum detector size needed to adequately stop the reference $\gamma$-rays, and provided a large enough count rate. To reduce cost the smallest effective crystal volume would be chosen. The original PMT considered for the LED monitor was half an inch diameter. Geant simulations were conducted for cylinders half an inch wide with three different lengths, 0.5 inches, 1.0 inches, and 1.5 inches. The results of the simulations are summarized in Table 3.6.

<table>
<thead>
<tr>
<th>Crystal Length (Inches)</th>
<th>Number of Incident Photons in Photopeak (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>25.1</td>
</tr>
<tr>
<td>1.0</td>
<td>34.5</td>
</tr>
<tr>
<td>1.5</td>
<td>37.5</td>
</tr>
</tbody>
</table>

Table 3.6: Geant results for varying crystal sizes.
From the information provided by the Geant simulations an estimate was made of the LED monitor reference source trigger rates. For a distance, $d$, of 2 inches and a cylinder diameter, $a$, of 0.5 inches half the angular size would be $\theta = \arctan \left( \frac{a/2}{d} \right) = \arctan \left( \frac{1.27 \text{ cm}/2}{5.08 \text{ cm}} \right) = 0.125 \text{ rad}$. Using this value the detector angular area may be calculated. The radioactive source is to the side of the detector so that the cylinder looks like a box as in Figure 3.12. The box shape in the side view makes calculating the angular area easy and is equal to, $(2 \times 0.125 \text{ rad})^2 = 0.0625 \text{ rad}^2$. Dividing this number by $4\pi \text{ Sr}$ gives the fraction of angular coverage by the detector. If this fraction is then multiplied by the activity of the radioactive reference source then the rate of event detection is obtained. Assuming a 1 $\mu$Ci source the detection rate is,

$$\frac{0.0625}{4\pi} \times \frac{3.7 \times 10^{10} \text{ Bq}}{1 \times 10^6} = 0.00497 \times 37000 \text{ Bq} = 184 \text{ Hz.}$$

Only a fraction of these would end up in the photo peak (See Table 3.6). Using the smallest simulated detector size of 12.7 mm $\times$ 12.7 mm the photo peak acquisition rate at a distance of 2 inches from a source of 1 $\mu$Ci would be 46.2 Hz. A rate of a few Hz is acceptable for the statistical needs of the LED monitor detector. Thus the above calculation indicates that the smallest and least expensive detector size is acceptable for the monitoring system. It is also beneficial to keep the detector volume small as Gadolinium has a very large neutron absorption cross section for low neutron energies ($\leq 1eV$). The larger the detector is the more background neutron events there would be in the data.

### 3.4.3 Detector Design and Testing

Once the type and size of the scintillator was determined the entire detector package was designed. Components for the LED monitor detector are made by the Hamamatsu Corporation. The base used is the E974-22 which has a E678-12H socket. The PMT is a model R1450 ten stage tube. The diameter of the PMT is 19 mm or $\frac{3}{4}''$ with an active area width of 15 mm. Because of the diameter difference between the PMT and the GSO crystal a method of coupling the components
Measuring the Angular Size From a Distance $d$

Figure 3.12: Angular size of LED monitor detector.

together is needed. Figure 3.13 shows the acrylic sheath that the GSO crystal sits in. The Diameter of the acrylic sheath matches that of the PMT. The two pieces are optically coupled together with silicone rubber and placed inside an plastic detector tube. An outline of the components in a LED monitor detector is shown in Figure 3.13.

Figure 3.13: LED monitor detector (left) and a GSO sheath (right).

All four LED monitor detectors were assembled and tested at the University of Saskatchewan before use at DFELL. The purpose of the test was to confirm the proper function of the detectors, and to establish an operational voltage setting for the LED pulser and the PMTs. During the tests a $^{22}$Na radioactive source was used to determine if the photo peak predicted by the Geant simulation
appeared on the ADC histogram. All four detectors passed these tests. Clear photpeaks were acquired from the radioactive source and the LED peaks were obtained as well. Figure 3.14 show a typical example for the GSO photon full energy peak on the left and the LED peak on the right. From left to right the structures in the GSO absorption spectrum are the 511 keV Compton edge, the 511 keV full energy peak, the 1.27 MeV spectrum, and the small bump on the end of the spectrum corresponds to the 1.27 MeV full energy peak. The LED peak on the right in Figure 3.14 is Gaussian as expected from photon statistics. The voltage settings used in the trials are given in table 3.7.

Table 3.7: Voltage settings for LED monitor preliminary tests.

<table>
<thead>
<tr>
<th>Detector #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulser Setting (V)</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td>PMT Setting (kV)</td>
<td>1.31</td>
<td>1.50</td>
<td>1.50</td>
<td>1.55</td>
</tr>
</tbody>
</table>

3.4.4 Containment Box for the Monitor

Once the size of a LED monitor detector was established a containment system for the detectors and a radioactive source was made. The current Blowfish neutron detection array required four LED
monitor detectors, however the design was made to accommodate six detectors. The extra two detectors would fulfill the requirements of any future expansion of the Blowfish array. Figure 3.15 has top and side views of the LED monitor box construction diagrams. The box for the detectors has sliding rails that the detector housings position into. There are spacers for two different configurations, four detectors and six detectors. The different configurations are an attempt to keep the detectors in use as equidistant from the radioactive source as possible. This is done to keep the radioactive source detection rate as equal among the detectors as possible. The radioactive source sits on a post in the middle of the box at the front end where the GSO crystals are sitting. The radioactive source is included in the box to give the energy reference peak needed in the gain calibration calculation (See Figure 1.9). Other components shown in the diagrams at the front and rear of the box are adapters to get signals in and out of the box. The adapters at the front of the box are for the LED fiber coupling so that the reference LED light can get into the detector. The pairs of adapters at the rear of the box are to supply high voltage to the detectors and to provide a signal output.

Figure 3.15: LED monitor box construction diagrams.
3.4.5 Optical Attenuators

During Blowfish operations with low PMT gains it is necessary to attenuate the LED optical signal reaching the LED monitor PMTs. This is because the monitor detector high voltage can not be adjusted in conjunction with the array voltage. The monitor detectors must have a steady voltage to keep the radioactive photopeak of 662 keV within a usable range. Therefore during this type of measurement where the Blowfish array has a lower PMT gain than the LED monitor detectors, the amplitude of LED light is attenuated to prevent the signal from going off scale (See Figure 3.16). To bring down the light intensity levels to something that is usable for the LED monitor detectors several optical attenuators are attached to the fibers going into the LED monitor box connections. A batch of 6 optical attenuators were made and the attenuation factor for each fiber is listed in Table 3.8. The attenuation these optical connections provide is from the inherent light loss from a fiber connection outlined in section 2.4.8. The attenuation factor listed in Table 3.8 was determined by attaching a fiber to a prototype detector and repeatedly measuring the LED light peak location on an ADC. The measurements alternated with the optical attenuator inserted and then without any additional attenuation. The locations of the LED peaks were averaged for each case and then the following formula was applied to determine the attenuation factor,

\[
\text{Attenuation Factor} = \frac{(\text{Raw LED Average} - \text{Pedestal}) - (\text{Attenuated LED Average} - \text{Pedestal})}{(\text{Raw LED Average} - \text{Pedestal})} = \frac{(\text{Raw LED Average}) - (\text{Attenuated LED Average})}{(\text{Raw LED Average} - \text{Pedestal})}
\]
3.5 Fiber Optic Cable

The fiber optic cable used in the gain monitoring system must fulfill several requirements. The fiber must be capable of transporting visible light, it must be flexible with consistent light transmission after repeated bending, and the cable must also be multimodal so that a large portion of the light is accepted into the fiber and transported to the PMT. The two possible candidates are step index or graded index fibers. A step index fiber fiber was chosen for the gain monitor because large core plastic fibers provided the best light collection of incident light. At the time of writing large core plastic fibers were not available with a graded index profile.

3.5.1 Eska GH2001 Step Index Fiber

The fiber optic cable used in the gain monitoring system is the Eska GH2001 step index fiber made by Mitsubishi Rayon. [Mit05] The specifications of the fiber are given in Table 3.9. The most important numbers to note are the transmission loss, 0.15 dB/m, and the numerical aperture, 0.5. These two numbers will determine the intensity of light that enters the fiber and the amount of light intensity lost traversing the fiber.
### Table 3.8: Optical attenuation factors for LED monitor inserts.

<table>
<thead>
<tr>
<th>Attenuator #</th>
<th>Attenuation Factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>69</td>
</tr>
<tr>
<td>2</td>
<td>66</td>
</tr>
<tr>
<td>3</td>
<td>62</td>
</tr>
<tr>
<td>4</td>
<td>72</td>
</tr>
<tr>
<td>5</td>
<td>78</td>
</tr>
<tr>
<td>6</td>
<td>72</td>
</tr>
</tbody>
</table>

![Figure 3.17: An example of a ST connector and adapter.](image)

### 3.5.2 Fiber Optic Bundles

The fiber optic bundles for the gain monitoring system were made at the University of Saskatchewan. The Aluminum parts of the fiber bundle were made by the Department of Physics Machine Shop. The end of each fiber is crimped into a ST connector for quick removal and attachment of fibers to the detector packages. A picture of the ST connector and adapter type is given below in Figure 3.17.
Table 3.9: Properties of the Eska GH2001 fiber optic cable.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Step Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive Index (Core)</td>
<td>1.49</td>
</tr>
<tr>
<td>Refractive Index (Cladding)</td>
<td>1.40</td>
</tr>
<tr>
<td>Numerical Aperture</td>
<td>0.5</td>
</tr>
<tr>
<td>Transmission Loss</td>
<td>0.15 dB / m</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>40 MHz / 50 m</td>
</tr>
<tr>
<td>Operation Temperature</td>
<td>-55 → 85 °C</td>
</tr>
<tr>
<td>Fiber Diameter</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Core Diameter</td>
<td>0.48 mm</td>
</tr>
<tr>
<td>Jacketing Material</td>
<td>Polyethylene</td>
</tr>
</tbody>
</table>

The length of all 30 fiber strands in each bundle are 8.00 ± 0.02 m. This includes the length of the fiber that is enclosed by the aluminum bundle rod. Using equation 2.32, the signal attenuation by a 8 m fiber can be calculated with the information provided in Table 3.9. Rearranging the equation gives, $P(L) = P(0) \times 10^{-\alpha L/10}$. Inserting the values we find, $P(8) = 0.758$. Thus for the 8 m fiber there is a 25% reduction in light from the initial intensity to the final intensity. This is an acceptable amount of signal loss and the remaining light is sufficient to operate the system. Figure 3.18 shows one of the six fiber bundles that were made.

### 3.5.3 Fiber Bundle Component Tests

The fiber transmission intensities were measured for each bundle to determine the attenuation variations from fiber to fiber. Each fiber bundle and LED box have a number stamped into the
aluminum to make specific pairs. The parts must remain in pairs as small differences in the construction machining make the fiber bundles specific to a particular box. Once the fiber bundle and LED box are in position, data collection would begin with a LED pulsing rate of 100 Hz. Data collection would continue until the ADC histogram obtained several thousand counts in the LED peak. The percentage differences were then calculated by averaging all the peak locations for each fiber and then applying the formula \( \frac{\text{Fiber Peak} - \text{Average}}{\text{Average}} \times 100 \) to find the percent difference from the average for each fiber. Tables and plots of the fiber differences are in Appendix B. This process was able to identify fibers that were significantly different from the average. The brightest fibers can be used to supply light to detectors with poor optical connections. The fibers with the weakest light intensity are also useful. Such fibers may be used for supplying less light intensity to detectors with the best optical connections. If the average light intensity of the entire bundle is too high then LED Bundle Attenuators are used.

### 3.5.4 LED Bundle Optical Attenuators

The fiber bundles were designed with a removable cap (See Figure 3.9) so that an optical attenuator may be placed between the LED light source and the fibers. Figure 3.19 shows the circular
translucent disks that fit into the bundle cap and are half an inch in diameter. The reason the attenuators are used is so that the LED light source may be operated at high voltages where the light resolution is the best (See Figure 3.7). The better the resolution of the LED the less uncertainty there is in the LED peak location. Thus the least amount of error in the LED measurement can be achieved by running the LED with high voltages and then attenuating the emitted light to a useful intensity. The plastic disks are the attenuators that bring the light intensity down to a usable value. The plastic disks are made from a translucent report cover and file folder and are \( \sim 0.5 \) mm thick.

![Figure 3.19: Light attenuators for the fiber bundle.](image)

### 3.6 Detector Modifications

For the gain monitor to work, a method of delivering the LED light to the detectors on the *Blowfish* array is needed. This is done by inserting a section of fiber optic cable into the light guide of the detector package. The fiber runs from the attachment point in the light guide down the length of the detector to the base back panel where the connectors are. An ST connector, which is a removable connection point for two fibers that couples them together and mechanically isolates them from unwanted movements, is crimped on to the end of the fiber and inserted into a ST adapter locked into the base panel. The fiber optic cables from the LED can be easily attached using the other side
of the ST adapter completing the optical link from the LED to the detector cell (See Figure 3.20).

Figure 3.20: Modified light guide diagram and a ST adapter.

For a more detailed description of the detector upgrade process see Appendix A. At the same time that the detectors were modified for the gain monitoring system, all 88 detectors received new PMTs and bases.
Chapter 4

Gain Monitoring System Implementation

4.1 Integration of the Gain monitoring System into the Blowfish Array

Completing construction and testing of the gain monitoring system was only the first step. Once the device is ready for operation it does not become useful until it is properly integrated into the Blowfish array. The process of placing gain monitor components onto the array must be done in such a way that access to other components is not restricted, and all cables are organized in a tidy fashion away from immediate harm. The following sections outline the integration of gain monitoring components into and around the Blowfish array and the results of several system trials.

4.1.1 LED Box Placement

The LED boxes were mounted on the Blowfish array using L brackets. Holes were drilled between rings 3 and 4 on the array for attachment points. One side of the bracket was bolted to the Blowfish arm and the other to the top of the LED box. Only four of the eight detector arms were needed for
LED box placement as one box services two arms of the array. The arms chosen for attachment points were 1, 3, 5, and 7. They received LED boxes 1, 3, 5, and 2 respectively from the 6 LED boxes constructed. Pictures of the LED box mounts are in Figure 4.1.

4.1.2 Placement of the BNC 555 Pulser

The LED voltage supply comes from a BNC 555 benchtop pulser. The pulser was not put on the array or the frame due to the size of the pulser, but was placed in a electronics rack adjacent to the array. This keeps the BNC 555 pulser, which is an expensive piece of equipment, out of harm’s way and places it near the cooling fans. The voltage pulses travel to the LED boxes through four identical 43° cables. The cables are long and not tied down as several feet of slack is required to rotate the array 180° around the φ axis.

Figure 4.1: Mounting position of a LED box.
4.1.3 Fiber Bundle Placement

Before the fiber bundles could be put on the detector array sorting is required. Each fiber was untangled and looped into a protective sheath of vinyl. The protective sheath was made from a segment of tubing that was cut along the outer most edge and stapled together. The far right picture in Figure 4.2 shows a bundle separated into individual strands and wrapped into sheaths. Once the sorting process was completed the bundle rod was inserted into the LED box and fibers were passed through conduits made of cable ties to the designated detectors.

The detector-fiber assignments were determined by testing all 88 detectors with the same fiber. This created a map of which detectors had the best and the worst optical connections. The brightest fibers were paired with the worst optical connections and so on. The fibers from the LED box are long enough to reach any detector on the arm. Depending how close the detector is to the LED box there is additional fiber length that needs to be kept neatly out of the way. This was done by placing the protective sheath at the locking point between the detector and the metal frame, and winding the extra length into the sheath. Figure 4.2 shows two examples of fibers passing through cable tie conduits into protective sheaths at the locking pins of the detector. The reason all the fibers are the same length is to keep the signals simultaneous.

After all 88 detectors received a LED fiber the remaining fibers, 8 fibers per LED box, are attached to the LED boxes using cables ties. These left over fibers are used to replace damaged and problematic fibers when needed.
4.2 System Tests

The tracking capability of the gain monitor was tested by changing voltage values to the \textit{Blowfish} detectors, the GSO monitor detectors, and the LED pulser in separate trial experiments. The first round of tests dealt with altering the \textit{Blowfish} detectors PMT high voltage by 10 V and 20 V in separate trials. The second set of tests dealt with the LED pulser voltages which were changed by 50 mV and 140 mV in two trials. The final round of tests dealt with changing the high voltage on the GSO monitor detectors by 10 V and then 20 V. The change in detector gain was measured throughout all the trials by the gain monitoring system and a radioactive source. Measuring the detector gain directly with a radioactive source and with the gain monitoring system allowed a
comparison to determine the accuracy of the gain monitoring system calculation.

The information extracted from the data at the end of each trial run was a reference Compton edge for Blowfish, a reference peak position for the GSO monitor detectors, and the LED peak positions for both Blowfish and the GSO monitor detectors. The reference photon energy, from independent radioactive sources, was 2614 keV or 968 keV for Blowfish, and 667 keV for the LED detectors. These photon energies give Compton edges of 2381 keV, 766 keV, and 482 keV. The Compton edge from the 667 keV photon was not located during the gain calculation as the GSO scintillator is dense enough to provide a full energy deposition peak which is used as a reference instead of the Compton edge. Once all the reference information is collected the gain of the detectors on the Blowfish array can be calculated using the gain monitoring calculation outlined in Section 1.5. The measured gain from the radioactive source is then compared with the calculated gain.

During all of the system tests the pulser voltage output was measured by an ADC to determine if the voltage pulse was stable. It was determined that the voltage output was consistent and not of concern. A comparison of pulser voltage from different trials is shown in Figure 4.3. In the first plot the difference between the highest and lowest point, which are not successive points, is 26 bins out of about 2800 bins. This means that even if the two extreme points were successive the drift in voltage would still be less than 1%. In many cases the pulser drift error is less than 0.1%. The second plot, showing a separate set of tests, supports the pulser stability claim drawn from the first plot. From these data it is concluded that the BNC 555 LED pulser is a stable voltage source and will not cause apparent gain changes of any significance. However this stability of the BNC 555 pulser is not a necessity for the operation of the gain monitoring system. Even with larger voltage drifts the gain monitoring system would track the true detector gain by the change in LED light intensity caused by the voltage change. A stable pulser source merely simplifies the tracking process.
Figure 4.3: Two pulser stability tests each over a two day period. The Y axis has a full scale value of 57 mV for the left plot and 65 mV for the right plot.

All of the gain monitoring system tests performed are outlined in the following sections. The difference between the measured and the calculated gain values are examined, and the associated efficiency errors caused by the gain inaccuracies are determined.

4.2.1 PMT High Voltage Changes

Testing of the gain monitoring system started with an investigation of Blowfish detector PMT high voltage drift. High voltage changes will simulate gain changes in the scintillator/PMT system. For the first set of trials high voltage values were changed the same amount for all 88 detectors. Table 4.1 shows the various trials and the high voltage shifts from the standard operating voltages. The first test was a voltage change of 10 V first above and then below the initial detector setting. The second and largest voltage shift test was 20 V above and below the initial voltage setting. Larger voltage shift trials were not conducted because typical gain drifts do not exceed a 20 V equivalent.
Table 4.1: PMT voltage variation list for all 88 detectors.

<table>
<thead>
<tr>
<th>Run #</th>
<th>506</th>
<th>507</th>
<th>514</th>
<th>515</th>
<th>516</th>
<th>553</th>
<th>554</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔV (±1V)</td>
<td>-20</td>
<td>0</td>
<td>-10</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>20</td>
</tr>
</tbody>
</table>

Even though the voltage is changed the same amount for all 88 detectors the gain shift that the voltage change causes is different for each detector. The differences in gain shift comes from the fact that the operating voltages are different for each detector. The voltage settings ranged from about 1700 - 2000 V for the detectors. Hence a change of 10 or 20 V is a different fractional change of the total operating voltage for each detector. This will lead to differences in the amount each detector deviates from its original gain value. For testing purposes a variance in the gain drift is desirable because several different gain shifts are tested with a single voltage change.

Both the 10 V and 20 V high voltage change tests were also performed on the GSO monitor detectors and are listed in Table 4.2. The GSO monitor detectors use a smaller 10 stage PMT compared to the Blowfish detectors which have a 12 stage PMT. The GSO voltage trials tested if there is any difference in gain calculation error depending on which type of PMT undergoes a gain drift.

4.2.2 LED Voltage Changes

The second type of shift that the gain monitoring system must account for is changes in the LED intensity. The two primary sources of light intensity changes are aging of the LED, and pulser voltage changes. In either case the result is a fluctuation in the signal detected by the array. It is necessary to verify that the gain monitoring system can correct for these effects and account for them in the calibration. To determine if the gain calibration could adjust for light intensity shifts
Table 4.2: GSO monitor detector PMT trial voltage settings.

<table>
<thead>
<tr>
<th>Run</th>
<th>Ch 1</th>
<th>Ch 2</th>
<th>Ch 3</th>
<th>Ch 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>±1 V</td>
<td>±1 V</td>
<td>±1 V</td>
<td>±1 V</td>
</tr>
<tr>
<td>424</td>
<td>-1600</td>
<td>-1600</td>
<td>-1600</td>
<td>-1600</td>
</tr>
<tr>
<td>425</td>
<td>-1600</td>
<td>-1590</td>
<td>-1600</td>
<td>-1610</td>
</tr>
<tr>
<td>426</td>
<td>-1600</td>
<td>-1580</td>
<td>-1600</td>
<td>-1620</td>
</tr>
<tr>
<td>427</td>
<td>-1600</td>
<td>-1570</td>
<td>-1600</td>
<td>-1630</td>
</tr>
<tr>
<td>428</td>
<td>-1600</td>
<td>-1600</td>
<td>-1600</td>
<td>-1600</td>
</tr>
</tbody>
</table>

several trials were done in two separate tests with half of the LEDs subject to voltage alterations. In the first set of trials changes in voltage were first done in increments of 140 mV. A single voltage increment of 140 mV causes a large shift in LED intensity and is a limiting case. The second set of trials with 50 mV shifts are a more reasonable test variation for the operation of the system during an experiment. Larger voltage shifts were not investigated due to what is known of pulser stability and the slow process of LED aging.

Throughout the system tests the voltage of two of the LEDs were kept constant as a reference. The starting voltages for the LEDs were different between the 140 mV trial and the 50 mV trial because two different radioactive source energies were used to test more than one Blowfish configuration. The 140 mV tests used a 968 keV reference and the 50 mV tests a 2614 keV reference. Table 4.3 lists the voltage setting of LEDs for the 140 mV trials and Table 4.4 lists the LED voltage settings for the 50 mV trials.
Table 4.3: LED 140 mV trial voltage settings.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Ch 1 ±0.01 V</th>
<th>Ch 2 ±0.01 V</th>
<th>Ch 3 ±0.01 V</th>
<th>Ch 4 ±0.01 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>557</td>
<td>3.43</td>
<td>3.53</td>
<td>3.75</td>
<td>4.07</td>
</tr>
<tr>
<td>558</td>
<td>3.57</td>
<td>3.53</td>
<td>3.75</td>
<td>3.93</td>
</tr>
<tr>
<td>559</td>
<td>3.71</td>
<td>3.53</td>
<td>3.75</td>
<td>3.79</td>
</tr>
<tr>
<td>560</td>
<td>3.57</td>
<td>3.53</td>
<td>3.75</td>
<td>3.93</td>
</tr>
<tr>
<td>561</td>
<td>3.43</td>
<td>3.53</td>
<td>3.75</td>
<td>4.07</td>
</tr>
<tr>
<td>562</td>
<td>3.29</td>
<td>3.53</td>
<td>3.73</td>
<td>4.21</td>
</tr>
<tr>
<td>563</td>
<td>3.15</td>
<td>3.53</td>
<td>3.73</td>
<td>4.35</td>
</tr>
</tbody>
</table>

4.3 Results of Gain Tracking

Data from the system tests when analyzed can be separated into six categories. These categories are determined by which trial data are chosen in the analysis. There are two Blowfish detector trials, two GSO monitor detector trials, and two LED pulser variation trials. Details from each of these tests are included and discussed in the following sections. A detector map is included below (Table 4.5) and indicates which detectors are being supplied with light from the different LEDs. A sample data set is given in Appendix C showing the gain errors for all 88 detectors on the Blowfish array. Using the detector map it is possible to determine if any one LED bundle causes more or less error than its neighbors. The average error listed is for all 88 detectors on the Blowfish array (See Equation 4.1).

Average Gain Error = \[
\frac{\sum_{i=1}^{88} \sqrt{\left(1 - \frac{\text{Gain calculated}_i}{\text{Gain actual}_i}\right)^2} \times 100\%}{88}
\] (4.1)
Table 4.4: LED 50mV trial voltage settings.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Ch 1 ±0.01 V</th>
<th>Ch 2 ±0.01 V</th>
<th>Ch 3 ±0.01 V</th>
<th>Ch 4 ±0.01 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>307</td>
<td>3.00</td>
<td>3.85</td>
<td>3.70</td>
<td>3.20</td>
</tr>
<tr>
<td>308</td>
<td>2.95</td>
<td>3.85</td>
<td>3.70</td>
<td>3.25</td>
</tr>
<tr>
<td>309</td>
<td>2.90</td>
<td>3.85</td>
<td>3.70</td>
<td>3.30</td>
</tr>
<tr>
<td>310</td>
<td>3.00</td>
<td>3.85</td>
<td>3.70</td>
<td>3.20</td>
</tr>
<tr>
<td>311</td>
<td>3.05</td>
<td>3.85</td>
<td>3.70</td>
<td>3.15</td>
</tr>
<tr>
<td>312</td>
<td>3.10</td>
<td>3.85</td>
<td>3.70</td>
<td>3.10</td>
</tr>
</tbody>
</table>

Table 4.5: A list of detectors receiving light from each LED.

<table>
<thead>
<tr>
<th>LED 1</th>
<th>1 2 9 10 17 18 25 26 33 34 41 42 49 50 57 58 65 66 73 74 81 82</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED 2</td>
<td>3 4 11 12 19 20 27 28 35 36 43 44 51 52 59 60 67 68 75 76 83 84</td>
</tr>
<tr>
<td>LED 3</td>
<td>5 6 13 14 21 22 29 30 37 38 45 46 53 54 61 62 69 70 77 78 85 86</td>
</tr>
<tr>
<td>LED 4</td>
<td>7 8 15 16 23 24 31 32 39 40 47 48 55 56 63 64 71 72 79 80 87 88</td>
</tr>
</tbody>
</table>

4.3.1 Blowfish Detector PMT Voltage Shifts

The first group of trials considered PMT high voltage changes of the Blowfish detectors only. The run numbers from these trials were given in Table 4.1. The detector gain errors for the 10 V and 20 V trials were approximately the same. The average gain error for the 88 detectors on Blowfish is 0.84% with a standard deviation of 0.67%. The error for the Blowfish PMT variation trials comes within the 1% desired tolerance for the system. This indicates that on the whole the
energy calibration is well determined. A comparison between the average gain error with the gain monitoring system and without it is given in Table 4.6.

Table 4.6: The gain error and standard deviation of the monitoring system and the percent gain change with no correction for PMT voltage shifts is listed below.

<table>
<thead>
<tr>
<th>PMT Shift</th>
<th>Average Error</th>
<th>Stand. Dev.</th>
<th>Mean Uncorrected Gain Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 V</td>
<td>0.84</td>
<td>0.67</td>
<td>6.04</td>
</tr>
<tr>
<td>20 V</td>
<td>0.83</td>
<td>0.66</td>
<td>12.05</td>
</tr>
</tbody>
</table>

More details of the analysis results for the first trials are included in Appendix C. The tabulated results include the change in PMT voltage, the average detector gain error, the standard deviation, as well as the standard deviation of the mean. The list shows that for PMT voltage shifts of 10 V or 20 V the average error associated with the gain tracking system is small. This means the calculated detector gain from the monitoring system is on average close to the true value for these types of voltage shifts. The PMT gain shift does not have to be from a voltage change, which are irregular, for the system to be able to correct for it. When aging or damaging of the PMT causes gain changes the system could adjust for these as well. This is because the actual voltage value is never used in the calculation. Only the response of the PMT to the LED flasher light and the scintillation light determines the correction value. Therefore if PMT aging were to cause a gain drift, equivalent to a voltage change 20 Volts in magnitude or less, the gain monitor is able to find the correct gain. Averaging over all 88 detectors the gain of the array is known to within an error of less than 1%.
4.3.2 LED Voltage Shifts

The second group of trials consisted of changing the LED pulser voltage settings on two out of four LEDs. The run numbers and voltage changes from these trials were given in Table 4.3 for 140 mV LED shifts and Table 4.4 for 50 mV LED shifts. The voltage measurement accuracy during these trials was 10 mV. The results of trial run comparisons for the LED voltage shifts are located in appendix C. The the average detector error and the standard deviation are listed in Appendix C for 140 mV shifts followed by 50 mV shifts.

For the 140 mV pulser trials the average gain error is 1.51 % with a standard deviation of 1.31 %. This is about double the error that was found with the PMT voltage changes. For the 50 mV pulser trials the average gain error is 0.49 % with a standard deviation of 0.31 %. Thus the average error for the 50 mV trials is well under the target tolerance of 1 %, however this can not be said about the 140 mV LED trials which have average error over 1 %.

This result for the 140 mV pulser shifts, which is over the desired 1% tolerance, is not a problem for the gain monitoring system. The pulser stability tests shown in Figure 4.3 indicates pulser shifts are significantly smaller than 140 mV. A comparison between the average gain error with the gain monitoring system and without it is given in Table 4.7.

Table 4.7: The gain error and standard deviation of the monitoring system and the percent gain change with no correction for LED voltage shifts is listed below.

<table>
<thead>
<tr>
<th>LED Shift</th>
<th>Average Error</th>
<th>Stand. Dev.</th>
<th>Mean Uncorrected Gain Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>140 mV</td>
<td>1.51</td>
<td>1.31</td>
<td>7.00</td>
</tr>
<tr>
<td>50 mV</td>
<td>0.49</td>
<td>0.31</td>
<td>2.36</td>
</tr>
</tbody>
</table>
4.3.3 GSO Monitor Detector PMT Shifts

The third group of trials conducted involved PMT voltage changes of the GSO monitor detectors. The voltage variations of the four GSO monitor detectors are given in Table 4.2. The voltage variations during the trials were in 10 V increments to a maximum of 20 V above and below the operating voltage. The average gain error for the 10 V GSO monitor detector PMT trials is 0.43 % with a standard deviation of 0.34 %. The 20 V GSO monitor detector shifts have an average error of 0.59 % with a standard deviation of 0.48 %. A comparison between the average gain error with the gain monitoring system and without it is given in Table 4.8. Details of the individual tests are available in Appendix C.

Table 4.8: The gain error and standard deviation of the monitoring system and the percent gain change with no correction for GSO voltage shifts is listed below.

<table>
<thead>
<tr>
<th>GSO Shift</th>
<th>Average Error</th>
<th>Stand. Dev.</th>
<th>Mean Uncorrected Gain Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 V</td>
<td>0.43</td>
<td>0.34</td>
<td>2.01</td>
</tr>
<tr>
<td>20 V</td>
<td>0.59</td>
<td>0.48</td>
<td>3.67</td>
</tr>
</tbody>
</table>

The GSO trials resulted in an average error below the desired limit of 1 % within one standard deviation. The tests demonstrate that for standard operating voltage shifts the gain monitoring system is able to correct for differences in the GSO monitor detector PMT gains. Therefore the gain tracking of the Blowfish detector array will not be compromised by standard changes of the GSO monitor detectors.

The next step was to determine what the effect all of the afore mentioned gain uncertainties will have on the detector efficiency. The following sections outline results for efficiency calculations using the gain information determined throughout the system trials.
4.4 Effects of Gain Error on Detector Efficiency

This section outlines efficiency calculation results using the gain information determined in the previous section. Two separate cases are examined using light output spectra from 6 and 10 MeV neutrons interacting with BC-505. For each neutron spectra three different threshold energies are investigated. Figures 4.4 and 4.5 show the neutron spectra generated by the Geant simulation. Geant is a software simulation package for the interaction of particles and materials. [Gea94]

For the efficiency calculations a continuous function was needed. The curve fitting program Grace, distributed under the GNU general public license, was used to find a function representation of each data set. The neutron spectrum was separated into two parts, first the peak at low energy near the simulation threshold, followed by the flat portion of the spectrum.

Figures 4.4 and 4.5 show the neutron spectra generated by the Geant simulation. The continuous functions that best represent the simulated neutron spectra are listed in equations 4.4 and 4.5. These functions were used in the analysis and integrated using the formula

\[
\int_{x_0}^{x_2} f(x) \, dx \approx \frac{h}{3} [f(x_0) + 4f(x_1) + f(x_2)]
\]  

which is the second order numerical quadrature method also known as Simpson’s Rule. The step size used in the numerical integration was 0.1 keV.

The following two sections list the efficiency error results for 6 and 10 MeV neutrons. The analysis demonstrates that efficiency errors are a fraction of the gain errors in and around the 6 to 10 MeV
neutron range. The detector efficiency is defined in equation 4.3.

\[ \varepsilon = \frac{\int_{E_{thr}}^{\infty} N \, dE}{\text{Incident Neutrons}} \]  \hspace{1cm} (4.3)

Where \( N \) is the number of counts at a specific energy, the lower bound of the integral is the hardware threshold, and \( N \) is integrated over all energies above threshold.

The efficiency error quoted in the following sections is due to gain changes only and is defined in equation 4.4.

\[ \delta\varepsilon = \frac{\int_{E_{thr}}^{\infty} N \, dE - \int_{E_{thr}+\delta E_{thr}}^{\infty} N \, dE}{\int_{E_{thr}}^{\infty} N \, dE} \times 100\% \]  \hspace{1cm} (4.4)

Where \( \delta E_{thr} \) is the error in the gain value and is defined in equation 4.5.

ADC channel for the threshold

\[ = \text{Bin}_{thr} = \frac{E_{thr}}{\text{gain}} \]

Shifted threshold energy from a gain shift from \( g \) to \( g' \)

\[ E'_{thr} = g' \text{Bin}_{thr} = (\text{gain} + \delta\text{gain}) \frac{E_{thr}}{\text{gain}} \]

\[ = E_{thr} + \frac{\delta\text{gain}}{\text{gain}} E_{thr} \]

\[ \Rightarrow \delta E_{thr} = \frac{\delta\text{gain}}{\text{gain}} E_{thr} \]
4.4.1 Efficiency Error for 6 MeV Neutrons

![Neutron Light Output Spectra](image)

Figure 4.4: Geant spectra for 6 MeV neutrons in BC - 505 scintillator and fitting function.

Equation 49 below describes the spectra above in Figure 4.4. The exponential equation is used for the low energy end of the spectra close to threshold where there is an onset peak. The cubic equation is used for the majority of the data including the flat region and the shoulder ending the spectra. The fitting functions are used instead of the simulated data to eliminate the graininess of the finite data set.
\[ 53.34 - 45.189 x + 34.875 x^2 - 8.395 x^3 \]

\[ 0.5 \text{ MeV} \leq x \leq 3.1 \text{ MeV} \]

\[ 151.47 \exp^{(4.8973 \ x^2 - 6.90434 \ x + 0.09531)} + 24.04 \]

\[ 0.02 \text{ MeV} \leq x \leq 0.5 \text{ MeV} \]

The results for the 6 MeV efficiency calculations is listed below in Tables 4.9-4.11. The detector efficiency error is less than the gain error determined in the previous section for all three threshold values.

Table 4.9: Average efficiency errors in percent for 6 MeV neutrons with a 100 keV threshold.

<table>
<thead>
<tr>
<th>Voltage Shift Type</th>
<th>Mean</th>
<th>Stand. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (10V)</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>PMT (20V)</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>LED (140 mV)</td>
<td>0.17</td>
<td>0.14</td>
</tr>
<tr>
<td>LED (50 mV)</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>GSO (10V)</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>GSO (20V)</td>
<td>0.06</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Table 4.10: Average efficiency errors in percent for 6 MeV neutrons with a 200 keV threshold.

<table>
<thead>
<tr>
<th>Voltage Shift Type</th>
<th>Mean</th>
<th>Stand. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (10V)</td>
<td>0.13</td>
<td>0.11</td>
</tr>
<tr>
<td>PMT (20V)</td>
<td>0.13</td>
<td>0.11</td>
</tr>
<tr>
<td>LED (140 mV)</td>
<td>0.25</td>
<td>0.21</td>
</tr>
<tr>
<td>LED (50 mV)</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>GSO (10V)</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>GSO (20V)</td>
<td>0.09</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 4.11: Average efficiency errors in percent for 6 MeV neutrons with a 500 keV threshold.

<table>
<thead>
<tr>
<th>Voltage Shift Type</th>
<th>Mean</th>
<th>Stand. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (10V)</td>
<td>0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>PMT (20V)</td>
<td>0.22</td>
<td>0.17</td>
</tr>
<tr>
<td>LED (140 mV)</td>
<td>0.40</td>
<td>0.34</td>
</tr>
<tr>
<td>LED (50 mV)</td>
<td>0.12</td>
<td>0.08</td>
</tr>
<tr>
<td>GSO (10V)</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>GSO (20V)</td>
<td>0.15</td>
<td>0.12</td>
</tr>
</tbody>
</table>
4.4.2 Efficiency Error for 10 MeV Neutrons

Figure 4.5: Geant spectra for 10 MeV neutrons in BC - 505 scintillator and fitting function.

Equation 50 below describes the spectra above in Figure 4.5. The Gaussian equation is used for the low energy end of the spectra close to threshold where there is an onset peak. The polynomial equation is used for the majority of the data including the flat region and the shoulder ending the spectra. The fitting functions are used instead of the simulated data to eliminate the graininess of the finite data set.
\[36.4021 - 31.0331 x + 13.2215 x^2 - 2.20538 x^3 + 0.11871 x^4\]

\[0.09 \text{ MeV} \leq x \leq 6.0 \text{ MeV}\]

\[291.84 \exp\left(\frac{(x-0.049565)^2}{2 \times (0.0219267)^2}\right)\]

\[0.02 \text{ MeV} \leq x \leq 0.09 \text{ MeV}\]

The results for the 10 MeV efficiency calculations is listed below in Tables 4.12-4.14. As before the detector efficiency error is less than the detector gain error, and this will hold true for all neutron energies higher than 6 MeV.

Table 4.12: Average efficiency errors in percent for 10 MeV neutrons with a 100 keV threshold.

<table>
<thead>
<tr>
<th>Voltage Shift Type</th>
<th>Mean</th>
<th>Stand. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (10V)</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>PMT (20V)</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>LED (140 mV)</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>LED (50 mV)</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>GSO (10V)</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>GSO (20V)</td>
<td>0.03</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Table 4.13: Average efficiency errors in percent for 10 MeV neutrons with a 200 keV threshold.

<table>
<thead>
<tr>
<th>Voltage Shift Type</th>
<th>Mean</th>
<th>Stand. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (10V)</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>PMT (20V)</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>LED (140 mV)</td>
<td>0.13</td>
<td>0.11</td>
</tr>
<tr>
<td>LED (50 mV)</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>GSO (10V)</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>GSO (20V)</td>
<td>0.05</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 4.14: Average efficiency errors in percent for 10 MeV neutrons with a 500 keV threshold.

<table>
<thead>
<tr>
<th>Voltage Shift Type</th>
<th>Mean</th>
<th>Stand. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (10V)</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>PMT (20V)</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>LED (140 mV)</td>
<td>0.28</td>
<td>0.24</td>
</tr>
<tr>
<td>LED (50 mV)</td>
<td>0.09</td>
<td>0.05</td>
</tr>
<tr>
<td>GSO (10V)</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>GSO (20V)</td>
<td>0.11</td>
<td>0.09</td>
</tr>
</tbody>
</table>
4.5 Summary and Conclusions

The *Blowfish* neutron detector array was equipped with a monitoring system capable of measuring the gain of all 88 detectors during an experiment. The design of the new system was based on the distribution and monitoring of pulsed light to the 88 detectors from four LEDs. These LEDs are kept under constant observation by reference detectors next to a radioactive calibration source. The LED light source chosen for the system was the NSPB 310A made by Mitsubishi Corporation. The fast pulsing capability and brightness of the NSPB series met every requirement of the system. The driving voltage was supplied to the LED by a BNC 555 benchtop pulser. This pulser was able to supply a wide range of pulse widths on nanosecond scales, and was able to reach pulse output amplitudes up to and beyond the recommended maximum voltage value for the NSPB 310A LED. In addition to these operation characteristics the BNC 555 pulser had 8 independent output pods needed to independently adjust each LEDs pulse width and amplitude. Every detector on the *Blowfish* array was connected to a LED through a fiber optic bundle of Eska GH2001 step index plastic fiber. The large core diameter of 0.5 mm and steady light transmission after repeated bending made the GH2001 a favorable choice for the gain monitoring system. One of the bers from each of the four LED bundles was connected to a E974-22 Hamamatsu PMT with GSO scintillating crystal using an ST connector. The ST fiber optic standard was used throughout the array at every non-permanent fiber connection point. The operational capabilities of the gain monitoring system were determined through several sets of trial experiments.

For each trial the actual gain of the detector was measured by a radioactive source and was compared to the calculated gain predicted by the gain monitoring system. The detector gain error was determined by taking the difference between the calculated and measured gain values for each trial case. A summary of the detector gain error for each trial is given in Table 4.15. The majority of the tests showed the gain errors to be close to 1 % or less. The only exceptions were the tests
Table 4.15: Average gain errors in percent for all gain monitor tests.

<table>
<thead>
<tr>
<th>% Errors → Trials</th>
<th>Mean</th>
<th>Stand. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (10V)</td>
<td>0.84</td>
<td>0.67</td>
</tr>
<tr>
<td>PMT (20V)</td>
<td>0.83</td>
<td>0.66</td>
</tr>
<tr>
<td>LED (140 mV)</td>
<td>1.51</td>
<td>1.31</td>
</tr>
<tr>
<td>LED (50 mV)</td>
<td>0.49</td>
<td>0.31</td>
</tr>
<tr>
<td>GSO (10V)</td>
<td>0.43</td>
<td>0.34</td>
</tr>
<tr>
<td>GSO (20V)</td>
<td>0.59</td>
<td>0.48</td>
</tr>
</tbody>
</table>

with 140 mV LED pulser shifts. For these cases the gain error was more than double the target uncertainty of 1%. This does not present a problem however, as the stability of the LED pulser is such that 140 mV voltage variations will not occur (See Figure 4.3).

Once the detector gain errors were established the effect of these errors on detector efficiency was investigated for two neutron energies using three different threshold settings. Tables 4.9 - 4.14 list these results for 6 and 10 MeV neutrons with thresholds of 100 keV, 200 keV, and 500 keV. Detector efficiency errors were calculated to be a fraction of the gain error in this energy range. The average error in all six cases was below the target uncertainty of 1%. The highest average detector efficiency error calculated is 0.40% for 6 MeV neutrons with a 500 keV hardware threshold. This comes as no surprise as the efficiency errors are expected to get progressively worse as the detected neutron energy drops and detection threshold rises.

In conclusion the gain monitoring system provides an accurate measure of detector gain drift. The accuracy of the system decreases during large LED pulser voltage drift, however such large voltage changes are unlikely as the BNC 555 pulse generator is a stable voltage source. Measurements
conducted indicate that the BNC 555 LED pulser has voltage variations of the order of 30 - 40 mV measured over several days (See Section 14). The error in the detector efficiency caused by inaccuracies in the gain is on average a small amount for neutron energies in the range of 6 - 10 MeV. Since the associated errors decrease with higher particle energies the system tests confirm that the gain monitoring system can be used accurately for neutron energies higher than 10 MeV as well.

4.5.1 Future Work

Future investigation and testing of the gain monitoring system includes simulation of neutrons with kinetic energies lower than 6 MeV. Several more energy spectra may be examined to determine a mapping of the expected error associated with a given neutron energy and electronics threshold.

Additional trials with more than one voltage change would test the tracking capability of the system more rigorously. As well trials lasting an entire day would test how the errors change when the time between calibrations increases, and may indicate when the optimal time for calibration is.
References


[Gea94] GEANT version 3.21 *Detector Description and Simulation Tool*, CERN Program Library Long Writeup W5013, 1994


[Nnd02] National Nuclear Data Center.  Evaluated Nuclear Data File, Brookhaven National Laboratory, Upton NY, 2002


Appendix A

Detector Upgrade Manual

One of the essential tasks implementing the gain monitoring system was upgrading the existing detectors on blowfish to include a fiber optic cable and connector. At the same time the fiber optic upgrade was done the detectors were further improved by replacing old PMTs, bases and housings with new ones. Appendix A is the manual for the upgrade process that was done.
1. Remove Detector From the Array

Detectors may be easily removed from Blowfish by a single individual. To begin, the array must be rotated so the detector will not fall when its restraints are removed. To rotate Blowfish, the fastening screws at each end of the array must be loosened. The array will then move freely. When the array is in position, it should be clamped down again as removing a detector will change the weight distribution of the array. It is recommended that detectors are removed from the horizontal arms of the array.

Next, the hose clamp must be removed by unscrewing it. The hose clamp should be removed and put in a safe place or it will fall from the detector at the most inconvenient moment. Figure A.1 outlines the placement of the detector in the array. For a more detailed drawing of the detector package refer to Figure A.18.

Next, a hex-driver is required to loosen the four bolts holding the PMT housing. Once the four bolts have been loosened, the PMT housing is free. To remove the detector, carefully slide it out until the light guide is past the neighboring cells and the detector can be rotated. Rotate the detector so that the screws at the end of the housing line up with the appropriate notches in the arm. Pull the detector free. Then tighten the cylinders with the washers and re-fasten the hose clamp. The best place to store this equipment is from where it was taken.

Caution, when removing a detector, do not assume that the light guide is securely attached to the housing. If the cable ties have come loose the detector could fall apart.
Supporting the detector by the light guide when removing it will reduce the chance of damaging the detector.

2. **Remove Cell From Detector**

To remove the cell from the detector, all attachments between the cell and the detector housing must be severed. First, cut the cable ties that fit around the cell using wire cutters. The cable ties should be cut at the front face of the cell, where the two ties overlap, but great care must be taken not to create light leaks by puncturing the electrical tape or shielding paper (See Figure A.2). Pull the cable ties gently toward the far end of the plastic housing (away from the cell) to remove them from the setup completely.

A sharp utility knife can be used to cut the cell free of the detector housing. Take care to stay as close to the end of the housing as possible, and not to damage the light guide. Make a small cut in the tape between the light guide and the housing. After peeling back some of the tape, the end of the housing can be identified. Use the utility knife to cut the electrical tape all around the bottom of the housing, freeing the cell from the setup.
Figure A.2: A detector to be disassembled.

Note that the silicone cookie should be left on the end of the PMT inside the housing. If it is on the cell when the detector elements are separated, it should be moved to the photomultiplier tube. Also note that after the elements have been separated, cap the end of the housing with tin foil. This is done both to protect the cookie and to reduce the PMT’s exposure to light, which can be damaging.

3. Drill Hole for Fiber in Light Guide

The light guide hole can be made with either a drill press or a milling machine. The bits used were a 1/32 end mill, and two # 60 drill bits. A note of caution before starting this procedure is to test the chuck used to hold the drill bits to ensure that it does not have too much play in its motion. Some chucks meant for larger bits will wobble over a millimeter back and forth and are unsuitable for precision drilling. Due to the conical shape of the light guide around the PMT contact area an end mill bit is needed to make a flat surface which then can be drilled. The end mill bit cannot be used to drill the entire fiber hole because it is too small. No end mill bit commercially available is 1mm in size. Also the end mill bit is not very long so it could not reach the target depth of 8mm. The placement of the end mill ledge should be next to the flat PMT contact area leaving 1mm of space between the flat surface
and the end milled ledge (See Figure A.3).

Figure A.3: End mill and drill hole placement.

The reason that the hole is not placed any further away from the flat top of the light guide is housing space constraints. If the hole was placed further out, the \( \mu \) metal shield and housing would pinch the fiber when the detector is put together.

After the end mill had been used to create a flat drilling surface a # 60 drill bit is used to make a 8mm deep hole into the light guide. Following the hole being drilled another # 60 drill bit with the end ground flat is used to flatten the bottom of the hole. This is needed so that the maximum amount of light is transferred from the fiber to the cell. Note that no additional drilling is required with the second drill bit. It only shapes the bottom of the hole. If plastic material from the light guide is dug up during this process the drilling has gone too far and the hole is being deepend.

4. Dremel Fiber Slots in Base Electronics Board

To create space for the fiber inside the detector housing and to maintain a reasonable radius of curvature in the fiber, a slot must be made in the base electronics boards for the fiber to travel through. The slot should be positioned in one of the blank areas of the board, close to the fiber’s connecting point on the base (See Figure A.5).
Figure A.4: Dremeling base board.

Figure A.5: Electronics board slots.

Figure A.6: Dremel bits needed.
A Dremel tool with a tungsten carbide cutter bit can be used to create the slot in the board. See Figure A.6 for a picture of the Dremel bit. With the Dremel tool turned on a medium to high speed, apply light pressure with the side of the bit on the area of the board where the slot is desired to be. Continue applying pressure until the slot is of the desired depth. Note that caution should be taken with the Dremel to stay clear of any components, such as resistors or copper trace.

A small slot can also be made in the lower base electronics board that rests on the plug for the PMT. It can be made in the same fashion as the slot in the upper board, directly below the slot already in the upper board. Care should be taken not to remove very much of the black plastic of the plug. Once all dremeling is completed, use pressurized canned air to blow the dust off the base. During dremeling it will be necessary to clean the tungsten carbide drill bit periodically. It will be apparent when the bit needs cleaning as its cutting ability will become reduced. To clean the bit, use a utility knife or other thin edged object. Once the material collected in the grooves of the tungsten carbide bit is removed dremeling may resume.

5. Cut Detector Housing

The detector housing can be shortened by the needed 17mm using several methods. Either a band saw, a lathe, or a belt grinder can be used. The U of S prototype was made using a lathe. It should be noted that the lathe must have a sharp blade so only light pressure is needed for cutting. If too much pressure is put on the housing while being lathed the plastic may fracture. Before beginning the lathing process ensure the housing is mounted into the chuck straight to avoid any wobble.

If a housing is ground down to size a belt sander is recommended. The housing must be ground slowly so that the plastic does not melt, warping the finished product. It can be expected that the ground housing material will collect around the rim and will have to be cut
off later. When grinding the housing it should be rotated so that the ground surface is even. To do this easily an L shaped piece of metal (e.g. Al angle, iron angle) can be used. Clamp the metal down on the grinding belt work bench and rest the housing on it. A scribed mark on the metal is an easy way to ensure the appropriate amount it removed from every housing (See Figure A.7). Grinding should only be used to remove a short length from the housing, \( \leq 5\text{mm} \).

Figure A.7: Grinding housing.

The recommended way to shorten the housings is to use both a band saw and a belt sander. Apply masking tape around housing and mark the tape at the 245 mm point. Make the line about 1/3 or more of the way around the housing. If a felt tipped marker is used to make the line, ensure that the 245 mm mark falls on the edge of the marker line farther from the end of the housing that will be cut. The first \( \approx 15 \text{mm} \) of the housing can be removed using a band saw, taking care not to pass too near the scribed mark. The band saw cut will not leave an even edge so the belt sander is used to level the edge and trim the remaining 1 – 2\text{mm}. The housing should be rotated as it is being ground down to size. The long length of the scribed mark on the housing makes it possible to watch the progress. The housing is of the correct length once the scribed mark has been completely ground away. After waiting at
least one hour for the housing plastic to cool and harden, the excess plastic on the lip of the housing produced during sanding should be scraped away using a utility knife. The housing when finished should make contact with the light guide around the whole circle where they meet. A finished housing will be 245 mm long.

6. Dremel $\mu$ Metal Shield Supports

Once the detector housing has been shortened, the inner $\mu$ metal shield will protrude from the plastic housing when resting on the current $\mu$ shield supports. To provide a proper fit, the $\mu$ metal shield supports must be ground down. This is done using a Dremel tool with a grinding stone bit. See Figure A.6 for a picture of the Dremel bit used.

With the Dremel on at a medium to high speed, slide it into the housing. Grind a portion of each of the plastic notches off by placing the bit on top of the plastic notch (the edge closest to the center of the housing), and pressing down until the section has been ground flush with the inner wall of the housing (See Figure A.8). Use a flat-head screwdriver to scrape away any of the ground plastic shavings that remain.

![Figure A.8: Dremeling $\mu$ metal shield supports.](image-url)
The process of grinding off small portions of the plastic notches should be repeated until the $\mu$ metal shield cylinder rests approximately 1mm deep in the plastic housing (See Figure A.9). A flashlight can be used to inspect the notches to make sure they are even, or to identify which notches need to be filed for a correct fit.

Figure A.9: $\mu$ shield and housing alignment.

After the grinding process is complete, the housing should be cleaned. Plastic grounds generated in both the processes of shortening the housing and adjusting the mu shield supports will be present on the inside and outside of the housing. To clean the housing, use a large duster to take out the bulk of the plastic grounds, then use canned air to completely rid the housing of any remaining material.

7. Epoxy Fiber to Light Guide

To epoxy the fibers into the light guide, first scrape a small amount of white paint around the hole, so the epoxy can stick directly to acrylic. Then insert the fiber, 35cm in length, into the hole in the light guide. The fiber should be cleaned before gluing to ensure that the glue sticks to the fiber cladding and not dust or grit on the fiber.
Mix the epoxy on a non-absorbing surface such as tinfoil. Make sure that the batch is large enough to ensure that the mix ratio is correct. This will likely mean some wasted epoxy, but it is important to get the epoxy to cure properly.

Put a small dab of epoxy on the light guide at the point where the fiber protrudes from the drilled hole. Make sure that no epoxy gets onto the polished contact surface of the light guide. Repeat this for each of the light guides until the epoxy begins to harden. When the epoxy begins to harden, throw it away. A new batch will be needed for the rest of the light guides.

After ten to twenty minutes, the light guides may be carefully moved. They should not be handled for twenty-four hours to allow the epoxy to fully harden. After the epoxy has fully cured the bond strength of the epoxy should be tested by gently pulling up on the fiber until the corner of the detector cell lifts off of the table. Note that this test is not intended to test if the fiber can support the entire cell weight, but only to see if the glue joint has the strength to lift the cell onto an edge.

8. Attach ST Adapter to Housing

Push out the plastic plug in the back of the base. There are two teeth on the plug that need to be pushed in when the plug is being removed. A screwdriver or some other edged tool can be used to assist in removing the plug. When the plug is removed insert the ST adapter into the hole with the threads on the outside of the base. The threads must be on the outside so that the adapter could be detached from the outside if necessary (See Figure A.10). Always have the black plastic cap over the adapter when a connector is not attached to it.

Once the ST adapter is fastened in place all the connectors on the base will be lined with black caulking. The application of the caulking at the base of the connectors will prevent light from leaking into the detector unit. The caulking gun is too cumbersome to directly
apply the caulking to the connectors so some intermediate device is needed. Two options are a syringe, without a needle attached, or a tooth pick. The caulking is to form a ring around the connector where it makes contact with the base (See Figure ??). The ST adapter will require more caulk than the other connectors as the nut holding the adapter will have to be covered.

Figure A.10: Attaching ST adapter.

Figure A.11: Caulking PMT connections.
9. Crimp ST Connector to Fiber

Cut three pieces of tubing with diameters, 3/64”, 1/16”, and 3/32”. The small inner tube and the large outer tube should be the same length, ≈ 8mm. The Middle tube should be larger then the other two, ≈ 12mm. The middle tube is larger so that it acts as a protective sheath providing mechanical support (See Figure A.12).

![Figure A.12: Size of tubing.](image)

Using a pair of needle nose pliers and a utility knife cut the inner tube along one side as far as possible. Put the rubber tube on the pliers and complete the cut. Next using a pair of scissors cut away some of the tube until it will fit into the middle tube. Place the
tubes into one another and slide the fiber cable through them. Then slide the ST connector that will be crimped onto the fiber (See Figure A.13). Push the tubes into the ST connector firmly. Before the crimping is done make sure that some fiber is coming out of the end of the connector, it does not have to be very much. While holding onto the fiber crimp the ST connector twice down the length of the barrel (See Figure A.14). The crimp tool should be squeezed all the way down until the handle locking bar releases. If fiber is not held it is possible that the crimping action will pull the fiber into the connector so that a flush end is not possible. Once the crimping is done place the connector on the table and using a utility knife cut off the excess cable. The cut should be made flush with the ST connector ferrule.

10. Clean Silicone “Cookies” and Put Them on PMTs

The silicone “Cookies” can be cleaned using Isopropyl Alcohol and nonstick low residue wipes (e.g. Kimwipes). After the Cookies have been cleaned they should be stored in tin foil to keep dust and other particulates from settling on them. If the cookie that is removed is of very poor quality a replacement cookie should be put in its place.

To put the Cookie on the PMT, first rest the Cookie on top of the light guide. Touch one corner of the PMT to the edge of the Cookie and “roll” the PMT across the Cookie. The purpose of this is to ensure there are no air pockets between the PMT and the Cookie. The Cookie should come off of the light guide and stick to the PMT as it rolls across. Alternatively the cookie could be put on the PMT directly using a Kimwipe tissue. After cleaning the cookie with Isopropyl Alcohol press the cookie on to the PMT using the Kimwipe. Visually check to ensure there are no air pockets along the PMT and cookie contact area.

After the Cookie is on the PMT, cap the end with the Cookie using tin foil to protect the Cookie and reduce PMT afterglow.
11. **Insert Base-PMT-Cookie Into Housing**

Take the base-PMT-cookie unit and place it in the housing guiding the fiber through the dremeled slots. When in reach put the ST connector into the adapter and fasten it. Align the base holes with the housing holes and push the base gently into place. Replace the two locking pins. Tape around the seam where the housing and base meet.

![Figure A.15: Inserting the Base-PMT-Cookie.](image)

For the other end cut eight pieces of black electrical tape 3 inches long. While the housing is held in position (there should be some compression between the light guide and the Cookie) place the pieces of tape lengthwise across the light guide housing joint uniformly around the detector. Half the length of the tape should be on each side. Next wrap tape around the detector starting from the top of the eight pieces of tape down to half the cell length. The tape should not be stressed or stretched very much when applying. If the tape is stretched too much during wrapping the tape relaxes and pulls away from the cell collecting itself into the light guide-housing seem. The corners of the light guide must be well wrapped
12. Test for Light Leaks

To begin ensure that the high voltage source is off before you plug the detector into the supply. Once the high voltage cable is connected also connect the signal output to the oscilloscope. The oscilloscope settings should be around 2-5 mV divisions with 20 ns sweep time. Check that the trigger is set to detector channel and the threshold is about minus 3-4 mV. Before the light leak testing begins the two most common light leak points should be covered with tape. The SIG2 connector should have tape put over it and the ST adapter should have tape put over the protective rubber cap. Ensure that the tape covers the entire length of each port, and overlaps slightly with the caulking at the base of each port. This ensures that a continuous seal is formed, preventing leaks at the lower edge of the tape.

When the room lights are shut off the high voltage can be turned on. After connecting to a HV supply, step up the voltage in increments (-500V, -1000V, -1500V, -1800V). At -500 volts, there should be no events triggering on the oscilloscope. At -1000 volts, triggering events should occur approximately once every second or two. At -1500 volts, events should be rapid enough that a faint line becomes visible on the oscilloscope. At -1800 volts, the line should be slightly more intense. This is the minimum voltage that leak testing should be performed at, as some leaks have been observed that appear at -1800 volts but do not appear at -1700 volts. A higher voltage may be used if desired, but internal noise will be greater, which may obscure the signal produced by a light leak. With a flashlight probe around the detector cell while looking at the oscilloscope. A light leak will be a sudden increase in display intensity, and possibly a new peak will become visible, when the flash light passes over the leak. Cover the entire cells surface with the flash light from several angles. If a light leak is found cover the area with a piece of black electrical tape.
When it is reasonably certain that there are no light leaks, flash the room lights on and off a few times and see if the oscilloscope shows any signs of light leaks. During this last test the HV could be increased to $\approx -2000\text{V}$. 

13. **Attach Cable Ties**

For this step it is a good idea to first examine a housing that has been assembled already. Using a sharp knife, cut four rectangular pieces out of the tape holding the cell to the housing (down to the housing), so the cable ties can be epoxied right onto the housing. The rectangular slots must be positioned around the housing so that they are lined up with the flat faces of the cell. Using a template for this step is highly recommended. Do not cut off the tape around the bottom edge of the housing, as this would become a difficult light leak to repair.

![Cable Tie Placement Diagram](Figure A.16: Cable tie placement on housing.)

Score the exposed plastic of the housing with a utility knife. This needs to be done to create a rough surface such that the epoxy can make better contact between the housing and the cable tie.
It is important to note that the shortened cable tie in Figure A.16 must not stick out too far or it will get caught on the neighboring cell when the detector is being replaced. Also note that the length of the cable tie attached to the housing behind the light guide must be flush with the housing and covered with minimal amounts of tape. This is because detectors at the extreme angles of the arms in the Blowfish array (close to $\theta=0$ degrees or 180 degrees) need to be pushed far into the holes in the arm.

Once the detector has been prepared, cut two large cable ties to a length of 2 inches. The rest of the cable ties (they will have no connector end) should be saved for use on the other faces. Also cut four short pieces and one long piece of tape, to be used to hold the cable ties in place while the epoxy cures.

Before epoxying, make sure that the cable ties fasten together as required. The tracks on the tie should be epoxied face down in all cases.

Mix a batch of 90 minute epoxy and apply it to each place where the housing is bare. Position the cable tie into place and cover its cut end with a short piece of tape to hold it in place. This should be done for all four cable ties on the detector. Note that the short pieces of tape will be removed once the epoxy has cured. They are only used to hold the cable ties in place during the application and curing processes.

Once all four cable tie sections are in place, use the long piece of tape to secure the ties around the edge of the housing (the tape can overlap onto the light guide with no problems). Take caution not to overlap the small sections of tape already in place, as they will need to be removed after the epoxy has cured for the detector to fit properly in the array (they are only used to hold the cable ties in place during the application and curing processes). However if overlapping does occur the tape may still be removed with a utility knife. The last step of the epoxying process is to secure a large cable tie over the long piece of tape, as close to the
edge of the housing as possible. This cable tie will ensure that the epoxied ties are flush with the housing, and thus the detector will fit more easily into the extreme angles of the detector.

![Figure A.17: Final cable tie configuration.](image)

Once the epoxy has cured, remove the small pieces of tape from the epoxied cable ties. Use small cable ties to complete the support system holding the cell and the housing together. The cable ties can be tightened first by hand, and then using pliers, to ensure a snug fit around the detector. All four cable ties that are epoxied to the housing have a joint that must be tightened. Figure A.17 shows the joints for the long and short cable ties that must be tightened. Once every joint is tightened the cable tie ends should be clipped with scissors or wire cutters. Leave about 1 cm of cable tie length after the ratchet joint.

14. **Insert Detector into the Array**

The process of inserting a detector in the array is simply the opposite process as removing a detector. Slide the detector into one of the holes on Blowfish, making sure not to damage the detectors on either side. Do not worry too much about detector placement as it should be adjusted after all the detectors are in the array.
With the bolts loose enough that the metal cylinders can move, place the hose clamp around the cylinders. Tighten the hose clamp so that all the cylinders are in contact and applying pressure to the housing. Then tighten the bolts to hold the cylinders in place. It may be necessary to snip excess tie ends to get a detector past it neighbor. However not the entire end should ever be could off as tention of the cable ties may need to be adjusted.

Figure A.18: Detector diagram.
Appendix B

Fiber Optic Bundle Tests

The fiber transmission intensities were measured for each bundle to determine the magnitude variations from fiber to fiber. Each fiber bundle and LED box have a number stamped into the aluminum to make specific pairs. Every bundle was tested with the LED box of the same number. This change of light source is necessary due to the fact that each fiber bundle tube will not fit in all the LED boxes. Small differences in machining make the fiber bundles specific to a particular box. Albeit it may be possible to fit a single bundle into two or possibly three boxes if more force is applied, however never all of them. Once the fiber bundle and LED box are in position data collection would begin with a LED pulsing rate of 100 Hz. Data collection would continue until the ADC histogram obtained several thousand counts in the LED peak. The percentage differences were then calculated by averaging the peak ADC bin locations for each fiber and then applying the formula \( \frac{\text{Fiber Peak} - \text{Average}}{\text{Average}} \times 100 \) to find the percent difference from the average peak location for each fiber.
Table B.1: Relative light intensities for bundle #1.

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Figure B.1: Fiber profile for bundle 1.
Table B.2: Relative light intensities for bundle #2.

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Figure B.2: Fiber profile for bundle 2.
Table B.3: Relative light intensities for bundle #3.

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Figure B.3: Fiber profile for bundle 3.
Table B.4: Relative light intensities for bundle #4.

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Figure B.4: Fiber profile for bundle 4.
Table B.5: Relative light intensities for bundle #5.

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Figure B.5: Fiber profile for bundle 5.
Table B.6: Relative light intensities for bundle #6.

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Figure B.6: Fiber profile for bundle 6.
Appendix C

Trial Results From Gain Monitoring System Tests

Listed are the raw computer calculations from all of the trial run comparisons used in the analysis. The trials are grouped with respect to the test performed not the run number. Included at the end of the appendix is a sample data set from the Blowfish array detectors showing some typical numbers using runs 310 and 311.

**PMT 10V Shifts**

507 & 514

Mean gain error 0.81

Standard Deviation of the mean 0.07

Gain Variance 0.45

Standard Deviation 0.67
515 & 516
Mean gain error 0.86
Standard Deviation of the mean 0.07
Gain Variance 0.46
Standard Deviation 0.67

**PMT 20V Shifts**

507 & 506
Mean gain error 0.83
Standard deviation of the mean 0.07
Gain Variance 0.44
Standard Deviation 0.66

**LED 140 mV Shifts**

559 & 560
Mean gain error 1.65
Standard deviation of the mean 0.16
Gain Variance 2.26
Standard Deviation 1.50

561 & 562
Mean gain error 1.25
Standard deviation of the mean 0.11
Gain Variance 1.12
Standard Deviation 1.06
562 & 563
Mean gain error 1.64
Standard deviation of the mean 0.15
Gain Variance 1.85
Standard Deviation 1.36

**LED 50 mV Shifts**

307 & 308
Mean gain error 0.37
Standard deviation of the mean 0.02
Gain Variance 0.05
Standard Deviation 0.23

308 & 309
Mean gain error 0.65
Standard deviation of the mean 0.04
Gain Variance 0.14
Standard Deviation 0.37

310 & 311
Mean gain error 0.38
Standard deviation of the mean 0.03
Gain Variance 0.09
Standard Deviation 0.30
311 & 312
Mean gain error 0.55
Standard deviation of the mean 0.04
Gain Variance 0.12
Standard Deviation 0.34

**GSO 10 V Shifts**

424 & 425
Mean gain error 0.60
Standard deviation of the mean 0.04
Gain Variance 0.15
Standard Deviation 0.39

425 & 426
Mean gain error 0.24
Standard deviation of the mean 0.02
Gain Variance 0.02
Standard Deviation 0.16

426 & 427
Mean gain error 0.47
Standard deviation of the mean 0.05
Gain Variance 0.21
Standard Deviation 0.46
GSO 20 V Shifts

424 & 426
Mean gain error 0.60
Standard deviation of the mean 0.05
Gain Variance 0.19
Standard Deviation 0.43

425 & 427
Mean gain error 0.58
Standard deviation of the mean 0.06
Gain Variance 0.29
Standard Deviation 0.53
Table C.1: Errors in gain values for all 88 detectors from runs 310 & 311 and in percent.

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