Towards Dual-Readout Calorimetry For Redtop Experiment

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ABSTRACT

TOWARDS DUAL-READOUT CALORIMETRY FOR REDTOP EXPERIMENT

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Department of Physics
Northern Illinois University, 2019
Prof. Vishnu Zutshi, Director

By virtue of peculiar properties of the eta (η) Goldstone boson, the study of its decays is very important. The rare decays of this meson can provide unique opportunities to probe several fundamental invariance principles of physics world. The REDTOP experiment aims at searching for Physics Beyond Standard Model (BSM) by studying such decays at a sensitivity of $10^{-10}$ or below, which requires $10^{12}$ or more η mesons. The REDTOP collaboration has designed a detector to produce and reconstruct such a large number of η mesons, which will make REDTOP a rare decay factory. The detector is designed to be minimally sensitive to the background and only records the processes of interest. One of the REDTOP sub-detector is the ADRIANO calorimeter which is a specific version of an optimized dual-readout calorimeter. This calorimeter consists of two active regions: optical standard lead-glass which generates exclusively Cerenkov photons, and scintillating plastic which generates scintillating signals. Present work is concentrated around prototyping of Cerenkov radiators and measuring the light output from those radiators using a test beam at Fermilab.
TOWARDS DUAL-READOUT CALORIMETRY FOR REDTOP
EXPERIMENT

BY

TILAK B. MALLA
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A THESIS SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE
MASTER OF SCIENCE

DEPARTMENT OF PHYSICS

Thesis Director:
Prof. Vishnu Zutshi
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Mike Figora whose technical support is instrumental in hardware works. Todd Fletcher for his help in electronic setups and Bryan for his help in preparing scintillating tiles.

Shasa whose quick experimental tests helped to make choices during tile preparation. Sergey Uzunyan whose help and scripts made it possible to collect and process the data at the test beam.

Prof. Evgueni Nesterov for allowing me to use his spectrometer to measure the reflectivity of paints, Gregg Westberg for measuring roughness of polished glass surfaces, Josh Schwartz for his help to use the mond-saw in Geology department to slice the glass-blocks, Jim Freeman for allowing to use his darkbox setup at Fermilab test beam facility and Karime Maamari for helping to collect data during the test beam.

Bisham Poudel for his remarkable suggestions, creative ideas, guidance and the support throughout my graduate study.

Dr. Corrado Gatto for his all-around guidance, providing the tools and all help and encouragement to move forward in the research works.

My thesis director, Prof. Vishnu Zutshi, for his sound professionalism, considerate heart, constant support and proper academic guidance throughout my graduate research work.
DEDICATION

I would like to dedicate this work especially to Ganesh Malla, my brother for his unconditional support, encouragement and love for many years now. Also this work is dedicated to my loving wife for her love and support and to my family.
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6.2 Pedestal for CH-2: ADC values stored against samples 0-499 are filled in the histogram and Gaussian function fitted at the tallest peak gives mean noise level.

6.3 Histogram to find 1PE ADC for CH-2 MPPC: 1PE signals correspond to the first Gaussian distribution on the left of tallest peak, which being minimum of electronic noise fluctuations.

6.4 Pedestal for CH-1: ADC values stored in samples 0-499 of ADC values are filled in a histogram; a Gaussian function is fitted on the tallest bell shaped distribution; the mean of Gaussian gives the mean noise level.

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CHAPTER 1

η MESON DECAYS AND THE REDTOP EXPERIMENT

1.1 Introduction to the η Meson

The η meson has some interesting properties. First, it is a Goldstone boson since all its additive quantum number are zero. Second, it is an eigenstate of the charge conjugation operator (C), parity operator (P), charge-parity operator (CP ) and G-parity operator (G = CR₂, R₂ is rotation about second isospin axis). The η state is identical to vacuum or Higgs boson except for parity, parity being negative for η. The expression: $I^G J^{PC} = 0^+ 0^{-+}$ depicts that η has its additive quantum number isospin, I = 0 and total angular momentum, J = 0 and eigenvalue of the operators P, C and G are -1, +1 and -1 respectively. Also, I = 0 implies that η is an isospin singlet state. Moreover, it is a unflavored light meson because it is made entirely out of linear combination of light quark-antiquark pairs $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ [1, 2, 3, 4].

1.2 Importance of η Meson Decays

All elementary particles tend to decay spontaneously to lighter mass species unless forbidden by some underlying conservation laws. As a consequence of the properties of η meson mentioned in the introduction section, all possible strong decays of η are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.
For example: $\eta \rightarrow 2\pi^0$ will not occur due to P, CP invariance. Similarly, electromagnetic decays are forbidden in lowest order by C invariance and angular momentum conservation. For example $\eta \rightarrow 2\pi^0 \gamma$ will not occur by C and angular momentum conservation. The consequences of the symmetries: that $\eta$ is a very narrow state (mean-life is increased) and hence the contributions from higher-order processes are enhanced by a factor of $\sim 10^5$; that $\eta$ decays are mostly free of Standard Model backgrounds for new physics search [2 4].

Properties of $\eta$ mesons provide a unique opportunity to probe fundamental conservation principles and to look for new particles or forces Beyond Standard Model (BSM) if $\eta$ could be produced in excess of $10^{12}$. With a sample size of $\sim 10^9$, WASA-at-COSY were able to study $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ decay to look at the degree of CP symmetry conservation in the reaction via the study of asymmetry of the distribution of angles between pions and electrons emission planes but the result of WASA-at-COSY lacks statistics to provide a definitive conclusion. This type of flavor conserving CP violation is not predicted in the framework of the Standard Model. Therefore, the definitive signal of such asymmetry could be a discovery of a process from new physics [1 5 6].

So far scientists have listed about 14 of these rare $\eta$ decay modes and each mode provides an unique opportunity to search for new physics. Moreover, by virtue of being light-weight particle, it tends to decay into a small number decay products, which is easier to detect experimentally. In summary, the $\eta$ meson is an excellent laboratory for exploring new physics at energies below 1 GeV [2 7].

### 1.3 REDTOP Experiment

**Rare Eta Decays with TPC for Optical Photons (REDTOP)** is a new experiment being proposed to Fermilab and CERN aimed at the study of rare $\eta$ decays. This experiment aims
to look for new violations of the fundamental symmetries. It will also improve the sensitivity level of key physics conservation laws by several orders of magnitude beyond those of previous experiments.

The REDTOP experiment is designed to produce above $10^{12}$ $\eta$s per year. Such a large statistics sample will allow measurement of processes suppressed below $10^{-10}$ level. The study of following decays for C and/or CP violation with a sample of $10^{12}$ $\eta$s will be definitive [7].

$$\eta \rightarrow \pi^+\pi^-\pi^0$$

Similarly, REDTOP will provide an enhancement of two orders in the recent limit of statistics obtained for the following decay:

$$\eta \rightarrow \pi^+\pi^-l^+l^-$$

This decay, with $l=e, \mu$, can test CP violation by measuring the angular asymmetry between the $(e^+, e^-)$ and pion pair decay planes.

The decay $\eta \rightarrow \gamma A'$, with $A' \rightarrow e^+ e^- \text{ or } \mu^+ \mu^-$, provides two opportunities for new physics. They include vector dark photons $A'$ from $e^+ e^-$ pairs. In addition, search for $e^+ e^-$ pair could support a postulated light gauge boson as a mediator of a fifth, milliweak force [1, 7].

To produce $\eta$ particles required by the experiment, REDTOP scientists propose using a continuous beam of protons which impinges onto a target. As a result of collision $\eta$ particles and many other kinds of particles will be produced as secondaries. Therefore, it requires a specially designed detector that will be insensitive to background of particles generated by collision [7].
1.4 REDTOP Detector

The REDTOP collaboration has designed a novel detector, Fig. 1.1, which contains three sub-detectors for the correct identification of all the particles produced by the rare decay of the $\eta$ meson. Two of these sub-detectors, Optical TPC (OTPC) and ADRIANO calorimeter, are under development. Fiber Tracker is the third sub-detector that will use the same technology already developed for the LHCb Upgrade. Components of the REDTOP detectors are briefly described below.

1.4.1 Components of the REDTOP detector

A sketch of the REDTOP detector is shown in Fig. 1.1. The outermost blue ring is solenoidal magnet of field strength 0.6 T. Its other components are briefly described below.

The Target Systems

The red disc in the center of the Fig. 1.1 represents the target systems, which consists of ten round foils of Beryllium or Lithium, each about 1 cm in diameter and $\frac{1}{3}$ mm thick. The foils are spaced 1 cm apart. The target systems are held inside a beam pipe made of either carbon-fiber or beryllium. The pipe will also help in maintaining the vacuum and support the fiber trackers from its external wall. A proton beam of intensity $10^{15}$ protons/s and kinetic energy of 1.8 GeV would produce about $2.5 - 5 \times 10^6 \eta/s$ or $2.5 - 5 \times 10^{12} \eta$ in one year [1, 8].
Figure 1.1: The schematic diagram of the REDTOP detector. Components of the detectors are labelled [8].
The Fiber Tracker

The Fiber Trackers are placed in between beam pipe and the aerogel, shown in the Fig. 1.1. The main purpose of the Fiber Trackers is to provide the vertices for the tracks that will be generated when the daughters of $\eta$ meson will travel through the Optical TPC. The proposed layout of Fiber Tracker for the REDTOP detector will consist of three superlayers positioned between the beam pipe and the aerogel. Each super-layer is composed by five mats of scintillating fibers of 250 $\mu$m diameter and read-out at each end by multi-channel Silicon photomultipliers. The technology used for making super-layers for REDTOP detector will be the same as that used by the LHCb Upgrade for its Fiber Trackers. The LHCb has measured the space resolution of $\sim 70 \mu m$ for each superlayer at a test beam [1].

The Optical Time Projection Chamber (OTPC)

The yellow dodecagon in the Fig.1.1 represents the OTPC sub-detector. There is 3 cm thick aerogel in the inner wall and rest of of the chamber is filled with inert gas like $CH_4$. As in a conventional TPC, a charged particle is deflected in the chamber by a solenoidal magnetic field. However, rather than using the ionization process to detect those particles, the Cerenkov effect will be used. The external wall of the chamber will be surrounded by the photo-sensors. When an electron or a positron with a $\beta$ above the Cerenkov threshold traverse the gas, it will not just radiate photons but its trajectory will also bend in the solenoidal magnetic field. The deflection of the trajectory will be measured from the corresponding pattern detected by the photo-sensors. The measured deflection will be used to calculate the transverse momentum, $P_t$ of the particle. Also, the positions and the directions of the particles are obtained from the patterns of the rings radiated (when the aerogel...
is crossed) and the points where the particles hit the photo-sensors. Slower particles like muons and pions produce the characteristic rings when they cross the aerogel but do not radiate in gas because of their $\beta = c/v$ ($v =$ speed of charged particle) being below threshold. Their kinematic parameters are also obtained from their corresponding Cerenkov rings. Moreover, the Cerenkov ring of electron is different from that of muon or pion for same energy, and in magnetic field the rings for electron and positron will be deflected in opposite direction. Hence, OTPC also gives particle identification (PID). Protons and pions produced at target by inelastic scattering are consistently below detection sensitivity of the OTPC. Furthermore, the magnetic field curls the trajectories of these particles and prevents them from reaching the calorimeter in significant numbers.

The Fig. 1.2 shows the track of a 100 MeV electron (red curve) when it travels through the gas in a 0.6 T magnetic field. Those cyan lines are the tracks of the optical photons generated and detected in the sensors surrounding the gas.

Figure 1.2: Trajectory (red curve) of a 100 MeV electron traveling in the OTPC under solenoidal magnetic field 0.6 T. The optical photons, generated by the electron, which travel along the cyan tracks [8].
The ADRIANO Calorimeter

**ADRIANO** stands for **A** **D**ual **R**ead-out **I**ntegrally **A**ctive **N**on-segmented **O**ption. This calorimeter is an implementation of the principle of dual-readout calorimetry which produces two complementary signals. Those two signals correspond to the Cerenkov signal which is produced in the lead-glass of high density \((\rho > 5.0)\) and high refractive index \((n_D > 1.8)\) and scintillation signal which is produced in the scintillating materials. For REDTOP study, those two signals are used for particle identification purposes [8].
2.1 Principle of Calorimetry

In particle physics, calorimetry has been established as a versatile and powerful technique for particle detection. Calorimeters detect particles by absorbing their energy in blocks of instrumented materials. The interaction of the incident particle with the detector produces a shower of secondary particles with successively decreasing energy. Calorimeters generate charge or signals in response to the energy deposited by the charged particles of the shower in the active parts of the calorimeter. The response of a calorimeter is used to reconstruct the energy of the incident particle. In other cases, these generated signals can be used to extract other information like the identity, the location of energy deposit and the direction of the particle. Therefore, calorimeters can provide almost complete information of the incident particles [9].

Moreover, hermetic or $4\pi$ calorimeters can account for missing energy from the particles that escape detection, like neutrinos. Hermetic implies that no energy escapes the detection, and $4\pi$ implies that the design of the detector is such that $4\pi$ steradians of solid angle around the interaction point is instrumented. The REDTOP detector is an example of quasi-hermetic calorimeter because 96 % of solid angle is covered. Calorimeters are also often used for trigger purposes, since they can provide fast signals, which are easy to process and to interpret.
An energetic particle may produce two types of showers in the calorimeter: electromagnetic (EM) or hadronic showers. Electrons, and photons produce EM showers. Charged hadrons ($\pi^\pm, p^\pm, K^\pm$) and neutral hadrons ($n, K_L$) produce hadronic shower and muons usually only generate a track through the calorimeter. These showers are discussed briefly in appropriate sections below.

2.2 Types of Calorimeter

Calorimeters can be broadly divided into two categories: electromagnetic calorimeters and hadronic calorimeters depending upon the type of particle showers would develop in them. They can be further classified according to their construction techniques into sampling calorimeters and homogeneous calorimeters. Sampling calorimeters consist of alternating layers of an absorber to reduce the energy of the incident particle, and an active medium that provides signal. Homogeneous calorimeters are built of only one type of material that performs both tasks, energy reduction and signal generation. It depends on the goal of the experiment to use a specific or combination of these calorimeters.

2.2.1 Electromagnetic Calorimeter

**Electromagnetic Shower.** Electromagnetic showers are produced by the electromagnetic interaction of the particles with the material of the calorimeter. Interaction of electrons and photons with matter can be described in terms of QED processes like bremsstrahlung, pair production, ionization, photoelectric effect, Compton effect etc. If electrons and photons of sufficiently high energy ($\geq 1$GeV) impinge on a block of material, secondary photons are produced by bremsstrahlung and secondary electrons and positrons by pair production.
respectively. These secondary particles can further produce other particles by the same mechanisms, thus giving rise to a cascade of particles with progressively decreasing energies. The number of particles in the shower increases until the energy of the electron component falls below a critical energy, where energy is dissipated mainly by ionization and excitation and not in the generation of other particles and showering stops [9].

Fig. 2.1 shows an EM shower initiated by a photon (\(\gamma\)) in a calorimeter. It produces \(e^+\), \(e^-\) pair; both \(e^+\) and \(e^-\) produce more branches by generating photons by bremsstrahlung; photons thus generated also produce \(e^+\), \(e^-\) pairs and so on until energy of the electron drops below critical energy [9].

![Figure 2.1: A typical EM shower](image)

Electromagnetic calorimeters can measure energy of a particle over a wide energy range. There are varieties of EM calorimeters that are used for different applications by their specialty. Semiconductor calorimeters provide relative energy resolutions (\(\sigma/E\)) of \(\sim 0.1\%\) in 1 MeV energy range in nuclear \(\gamma\) ray spectroscopy. Scintillating crystals are used to measure \(\gamma\) rays in the energy range from 1 - 20 GeV with energy resolutions of the order of 1 %. Though, sampling calorimeters are cheaper to build at low energies, their energy resolution are dominated by the sampling fluctuations. Sampling fluctuations represent fluctuations
in the number of different shower particles that contribute to the calorimeter signals. This fluctuation is enhanced by the fluctuation in the amount of energy deposited by individual shower particles in the active layers of calorimeter. Sampling fluctuation depends both on the sampling fraction -the ratio of active and passive material and on the sampling frequency -the number of different sampling elements in the region where the showers develop \cite{9, 10}.

Sampling fluctuations are the consequence of such a stochastic process and their contribution to the relative energy resolution, $\sigma/E$, is given by:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}}, a = 0.027 \sqrt{d/f_{samp}}$$ (2.1)

in which $d$ represents the thickness of individual active sampling layers (in mm), $f_{samp}$, the sampling fraction for minimum ionizing particles (MIPs), and $E$ is the particle energy in GeV. This expression fairly describes data obtained with a large variety of different non-gaseous sampling calorimeters \cite{10}.

### 2.2.2 Hadron Calorimeter

**Hadronic Shower.** Hadrons mostly lose energy by strong interactions with the material of the calorimeter. The first generation of particles in a shower consists of heavy fragments and components like protons, neutrons, charged pions, and neutral pions. Because of the charge independence of hadronic interactions, in each high-energy collision on average one-third of the pions produced will be $\pi^0$, but neutral pions will decay into two photons ($\pi^0 \rightarrow \gamma \gamma$) before having a chance to re-interact hadronically. Thus, hadronic shower contains EM component and non-EM component. $\pi^0$ starts electromagnetic shower immediately and transfers part of the hadronic energy to the EM component. As the number of energetic hadronic interactions increases with incident energy, the fraction of energy carried by EM
cascade also increases. Meanwhile, substantial amount of energy from hadronic collision also goes to photons and neutrons. But, only a fraction of photon energy will be recorded in measuring instruments, as most of these photons are emitted with a considerable time delay ($\leq 1 \mu s$). These delayed photons, soft neutrons, and binding energy produce a form of invisible energy. In general, if this invisible energy is detected it will be only at much reduced efficiency.

Fig. 2.2 shows development of a hadronic shower initiated by a neutron. Over one nuclear interaction length $\lambda$, first generation of particles: charged pions, heavy fragment and neutral pions are produced. Neutral pions generate EM showers and constitute the EM component of the hadronic shower and rest of the particles constitute non-EM component of hadronic shower.

Figure 2.2: A typical hadronic shower initiated by an energetic neutron in the material of calorimeter. First generation shows that hadronic shower has electromagnetic as well and hadronic components [11].

Hadronic calorimeters can be used to measure an energy range wider than an EM calorimeter possible could. For the purpose of calorimetry, the main difference between two hadronic shower components, shown in Fig. 2.2 is that some fraction of the energy con-
tained in the non-EM component does not contribute to the signals. This invisible energy may take large portion of the total non-EM energy, with large event-to-event fluctuations.

Figure 2.3: Fluctuation in electromagnetic fraction, $f_{em}$ of calorimeter from event to event gives a distribution around a mean value [10].

Moreover, the properties of the EM shower component also affect the energy resolution, the signal linearity and the response function of hadron calorimeter. The EM fraction varies from event to event as number of $\pi^0$ generated at hadronic interaction vary statistically from event to event, as shown in Fig. 2.3, and those fluctuations are large and non-Poisson. In addition, the average fraction of the total shower energy contained in the EM component increase with energy. The latter property represent signal non-linearity from EM component.

Calorimeter response can be defined as the conversion efficiency from deposited energy to generated signal. The responses of a given calorimeter to the EM component, $e$ and non-EM component, $h$ of a hadronic shower are usually different as a result of invisible energy and a variety of other effects. Also, the calorimeter response to showers is usually different from that to minimum ionizing particle (MIP). If $\frac{e}{h} \neq 1$, such calorimeters are called non-compensating and since their response to hadrons is energy dependent, they are intrinsically non-linear. If the calorimeter responses to the EM and non-EM components are recorded for many events, started by same hadron with identical initial conditions, those components
follow distribution functions as shown in Fig. 2.4. The average of corresponding distributions are denoted by $e$ and $h$. The calorimeter responses are normalized to the calorimeter response to MIP [10, 12].

Figure 2.4: The normalized (to MIP) distributions of calorimeter’s response to an EM and non-EM component of a hadronic shower: $h$ is the mean value of distribution of non-EM component represented by the blue curve and $e$ is the mean value of the distribution of EM component represented by the red curve [10].

### 2.3 Compensation in Calorimeter

Compensating calorimeters satisfy, $e/h = 1.0$ by design. Such calorimeters overcome the effects of non-compensation on the hadronic energy resolution, non-linearity and the associated calibration problems. However, there are major drawbacks of compensating calorimeters: compensating design that uses high-Z absorber materials works for high energy hadrons but compensation breaks down for low-energy hadrons; the need to detect low energy neutrons with high efficiency requires signal integration over a relatively large volume during relatively large duration of time.
2.4 Principle of Dual Read-out Calorimetry

The fluctuations in EM shower fraction spoils the hadronic energy resolution of non-compensating calorimeters and compensating calorimeters come with other drawbacks. Dual-readout calorimetry provides an alternative approach to eliminate the effects of such fluctuations in the EM shower fraction and avoids the use of compensation by design by measuring $f_{em}$ for each event. The Cerenkov mechanism provides a unique opportunity to achieve this. Calorimeter that use Cerenkov light as signal source almost only respond to the EM fraction of a hadronic shower. This is because the electrons/positrons through which the energy is deposited in the EM shower component are relativistic down to energies of $\sim 200$ keV. On the other hand, most of the non-EM energy in hadron showers is deposited by non-relativistic protons generated in nuclear reactions. Such protons generate signals in scintillating media. By comparing the Cerenkov and scintillating signals, the EM shower fraction can be determined. Also, the total shower energy can be reconstructed using the known $e/h$ value(s) of the calorimeter with those two kinds of signal [10, 12].

A dual-readout calorimeter produces two types of signals for the showers developing in it, a scintillation signal, $S$ and a Cerenkov signal, $C$. Both signals can be calibrated with electrons of known energy $E$, so that $<S> = <C> = E$ for EM showers, and the calorimeter response to EM showers, $R_{em} = <S>/E = <C>/E = 1$. For a given event, the hadronic signals of this calorimeter can be written as:

$$S = E[f_{em} + \frac{1}{(e/h)_s}(1 - f_{em})]$$

(2.2)

$$C = E[f_{em} + \frac{1}{(e/h)_c}(1 - f_{em})]$$

(2.3)
The total energy is the sum of an EM shower component \( f_{em} \) and a non-EM shower component \( 1 - f_{em} \). The contribution of the latter component to the reconstructed energy is weighted by a factor \( h/e \). When \( f_{em} = 1 \) or \( e/h = 1 \), the hadronic shower response is same as that for electrons: \( R = 1 \). However, in general \( f_{em} < 1 \) and \( e/h \neq 1 \), and therefore the hadronic response is different from 1. The reconstructed energy is thus different than \( E \). The dual-readout method works due to the fact that \( (e/h)_s \neq (e/h)_c \). The larger the difference between both values, the better \([10, 12]\).

Let us rewrite Eq. 2.2 and Eq. 2.3 as:

\[
S/E = f_{em} + \frac{1}{(e/h)_s}(1 - f_{em}) \tag{2.4}
\]

\[
C/E = f_{em} + \frac{1}{(e/h)_c}(1 - f_{em}) \tag{2.5}
\]

The \( f_{em} \) value for an individual hadron event is directly related to the ratio of the two signals, \( C/S \) and can be found by solving Eq. 2.2 – 2.3 or Eq.2.4 – 2.5 and using the known values of \( (h/e)_s \) and \( (h/e)_C \).

Graphical representation of these two equations is given in Fig. 2.5. It shows that the experimental data points for hadron showers detected with a dual-readout calorimeter are located around a straight (red) line in the \( C/E \) vs. \( S/E \) diagram. This line connects the points \([(h/e)_s , (h/e)_C \] , for which \( f_{em} = 0 \), with the point (1,1), for which \( f_{em} = 1 \).

The slope of the red line around which the hadron data points are clustered, i.e. the angle \( \theta \), only depends of the two \( e/h \) values, and is thus independent of the hadron energy.

\[
cot\theta = \frac{1 - (h/e)_s}{1 - (h/e)_c} = \alpha
\]
And the parameter $\alpha$ is independent of energy. Because of this feature, the scintillation and Cerenkov signals measured for a particular hadron shower can be used to reconstruct its energy in an unambiguous way:

$$E = \frac{S - \alpha C}{1 - \alpha}$$

Therefore, the dual-readout technique effectively takes advantage of both the measured signals to determine the EM shower fraction $f_{em}$. The actual $f_{em}$ distribution for showers produced in the absorption of a sample of hadrons of the same type and energy is not a factor that affects the energy measurement for that event sample. Since the correct energy is reproduced in for each case, a dual-readout calorimeter is linear for hadron detection [10].
2.5 ADRIANO Calorimeter

ADRIANO is a specific implementation of dual-readout calorimetry which uses optical grade lead-glass of total absorption type for generating exclusively Cerenkov signal, $C$. The lead-glass of high refractive index ($n_D > 1.8$), as radiator is most useful in high energy experiments, because of the excellent time resolution ($\sim 50 \text{ ps}$) which could be used as fast counting element. Also, Cerenkov effect is least affected by the changes in the ambient conditions because the refractive index of the material is least sensitive to such changes. The scintillating materials of different types can be used to generate scintillation signals, $S$. For REDTOP study, $C$ and $S$ signals are mostly used to determine the identity of the particles. As shown in Fig. 2.6, the $C$ and $S$ signals produced by the calorimeter for different particles of energy 100 MeV, as plotted, illustrate that the particles identities are resolved [13].

![Simulation result shows that the different particles of 100 MeV energies are identified with the scatter plot of scintillation and Cerenkov signals](image)

Figure 2.6: Simulation result shows that the different particles of 100 MeV energies are identified with the scatter plot of scintillation and Cerenkov signals [13].
ADRIANO Prototype

T1015 Collaboration has been doing the research and development work on ADRIANO calorimetry for many years. Several sets of prototypes have been built and tested in 2015 and three of them are shown in Fig. 2.7. The base unit of these prototypes consists of an individual parallelepiped cell of $40 \times 40 \text{ mm}^2$ cross-section and either 15 cm or 25 cm length. The cell consists of a sandwich of scintillating fibers and high density, optical grade heavy glass. The glass behaves as an absorber as well as an active medium, generating almost exclusively Cerenkov light with corresponding, $e/h \approx 3.5$. It is of the order of $\approx 1.5 - 1.8$ for scintillating material. The scintillation and Cerenkov sections of ADRIANO are optically separated [13].

Figure 2.7: Showing a few ADRIANO-I prototypes tested at Fermilab in 2015 by T1015 collaboration. The prototype block consists of lead-glass as Cerenkov signal generator and scintillating strips as generator of scintillating signals, read by WLS fibers [8].
ADRIANO2 Prototype

ADRIANO2, which is being built at Northern Illinois University (NIU), will be the second implementation of general dual-readout calorimetry. It is expected to go to test beam in December 2019. This version of prototype has a few modifications to the earlier version: plastic tiles of cross-section 10 cm $\times$ 10 cm is used to generate scintillating signals; each tile has four dimples on a surface; the read-outs will be taken by SiPMs by directly installing them on the top of the dimples. A general schematic diagram of lead-glass or plastic tile with SiPMs is shown in Fig. 2.8. The ADRIANO2 prototype will consist of 8 glass and 8 plastic tiles arranged alternately along with their carrier boards.

Figure 2.8: A modular structure of light radiators in ADRIANO2: the module represents both lead-glass and plastic scintillator tiles to be used as active materials to generate two types of signals.
3.1 Introduction to MPPC

Multi-Pixel Photon Counter (MPPC), also known as Silicon Photo-Multiplier (SiPM) is a highly photosensitive device. It can be used to detect extremely low light due to its very high internal gain ($\sim 10^5 - 10^7$). The source of this high gain is the Geiger-mode operation of avalanche photodiodes. An MPPC consists of an array of pixels, which are avalanche photodiodes (in Geiger-mode) in series with a quenching resistor. Fig. 3.1 (left) is a close-up view of an MPPC, showing array of pixels (small squares) and two terminals for a common-bias and a common-output; (right) shows the equivalent circuit of MPPC array with a dotted rectangle drawn around a pixel. Each pixel outputs a pulse signal when it detects one photon and signal output from the MPPC is the sum of the outputs from all the pixels.

Figure 3.1: (Left) A close-up view of a MPPC sensor is showing array of pixels and two terminals for common-bias and common-output; (right) equivalent circuit of an MPPC array represented as parallel combination of Geiger-mode APDs with their quenching resistors [14]
3.2 Avalanche Photo-Diode

An Avalanche photodiode (APD) is basically described as a p-n junction photodiode with a charge multiplication region. It uses the principle of photo-electric effect to convert incoming photons into photoelectrons. A photon having energy greater than the forbidden energy band gap \( E_g \) has finite probability to kick an electron in the valance band to the conduction band of the material of photodiode (Si, Ge or combination of III-IV materials of periodic table), producing an electron-hole pair in the material as shown in the Fig. 3.2.

![Energy bands in semiconductor](image)

**Figure 3.2:** Energy bands in semiconductor: a photon having energy in excess of forbidden band-gap, \( E_g \) can excite an electron from a valance band to a conduction band.

3.2.1 Working of Avalanche Photo-Diode

Working of an avalanche photodiode (APD) can be described by the help of a schematic diagram of Fig. 3.3. The middle panel of the diagram gives \( p^+ - p - n \) construction of an APD, where \( p^+ \) represent heavily doped region with p-type dopants and p and n are relatively lightly doped regions with p-type and n-type dopants respectively. The structure is externally reverse-biased by \( V_{bias} \), which together with the intrinsic electric field of the p-n junction, create an electric field whose strength profile is schematically shown in the top panel of the diagram. The field is maximum at the transition location from the p-doped
region to the n-doped region of a semiconductor mostly produced by the diffusion of charge carries mostly by thermal energy [15, 16].

![Schematic diagram of an APD](image)

Figure 3.3: Schematic diagram of an APD shows: (top) resultant electric field over the different regions of APD with highest field being in the depletion region; (middle) a typical scheme of construction different regions of APD with large depletion layer; (bottom) attenuation of two types of incident flux in the p-type material which depends on color of light [16].

The light is incident on the $p^+$ side of the APD. By virtue of photoelectric effect, incident photons can produce electron-hole ($e$-$h$) pairs. Materials with indirect band structure like silicon, the photon absorption process also involves a phonon. The characteristic depth of photon absorption depends on the type of the semiconductor and the wavelength of the light. The bottom panel of the diagram shows that flux $\phi$ of red photons attenuates less with depth compared to the flux of blue photons [16].

**Avalanche Process.** Lest us consider that an entry of a photon creates an electron-hole ($e$-$h$) pair close to or in the depletion region where the electric field is strong enough
to separate the pair and make the electron move toward the n region and the hole toward the $p^+$ region. In the depletion region, the likelihood of $e-h$ recombination is extremely small because the region lacks mobile charge. Typically the depletion widths are about one hundred times longer than the mean free path of the carriers between collisions [17].

For small value of the reverse bias, the energy losses from the collisions are small and only cause lattice vibrations. However, if reverse bias exceeds a specific limit, it causes the APD’s junction breakdown. The reverse bias applied across the diode in the latter case is called breakdown voltage, $V_{bd}$. For the reverse bias beyond $V_{bd}$, electric field in the depletion region accelerates the $e-h$ pair so significantly that both can create further $e-h$ pairs by the impact ionization with crystal lattices. The newly generated carriers are also immediately accelerated, leading to creating of further $e-h$ pairs. The chain reactions creating such pairs is called the avalanche process and this gives rise to the avalanche multiplication or commonly called gain.

Meanwhile, it should be mentioned that the avalanche mechanism does not occur at particular value of breakdown because there are avalanche events happening even far below breakdown. It is because not all free carriers participate in the avalanche effect at voltages beyond breakdown, while below breakdown, there may be a few free carriers that have enough energy to initiate the impact ionization. This phenomena started at low bias voltage quences because of low electric field, however, at higher reverse bias, the phenomena is well sustained. This statistical nature of avalanche process explains a sloping approach and smooth bend at voltage breakdown instead of a sharp edge in I-V curve of reverse bias photodiode, as shown in Fig. 3.4 [17].

**Geiger-mode of an APD.** Beyond breakdown, avalanche caused by an entry of a single charge carrier is self-sustained. As a result, current flows through the APD and its value depends on the over-voltage, $\Delta V = V_{bias} - V_{bd}$. The steepness of the curve in this region
Figure 3.4: Gain versus reverse bias voltage characteristic of a hypothetical avalanche photodiode [14].

implies that the magnitude of the current is very sensitive to $\Delta V$. The strong electric field in the avalanche region maintains $e-h$ plasma where both electrons and holes ionize comparably the lattice atoms. In a steady state, the number of newly created pairs is equal to the number of pairs collected at the electrodes. Thus, operating an APD beyond its breakdown voltage is known as Geiger - mode. The ratio of amount of output charge to the charge of incident charge carrier is called multiplication factor (M) or gain. The gain can also be calculated from input and output currents.

In the Geiger mode, the gain of APD is about $\sim (10^5 \text{ or } 10^6)$ and the magnitude of the output current is constant regardless of the number of input photons. To make any use of this gain, the avalanche process should start or stop as per need. A quenching circuit reduces the $V_{bias}$ and prevents APDs to latch indefinitely to the avalanche mode. This process is called quenching the avalanche [16].
3.3 Physics of Geiger-mode APD (GAPD)

Fig. 3.5 shows an equivalent circuit of Geiger-mode APD, GPAD (a pixel) under bias conditions. In the circuit, the GAPD’s capacitance \( (C_d) \) is initially biased at \( V_{bias} \) while the conceptual switch is open. Once an \( e-h \) pair is generated within the depletion layer, the conceptual switch closes, and \( C_d \) begins to discharge through GAPD’s series resistance \( R_s \) with a surge in current flow. Meanwhile, the potential difference, \( V_d \) across \( C_d \) exponentially decreases towards the breakdown voltage, \( V_{bd} \) which weakens the avalanche process \[16\].

![Equivalent circuit of a GAPD](image)

Figure 3.5: Equivalent circuit of a GAPD: quenching of avalanche is achieved by the quenching resistor, \( R_q \). The circuit within dotted line represents an equivalent circuit of an APD.

The equivalent circuit of Fig. 3.5 is used for the circuit analysis as given below:

Applying Kirchhoff’s junction law at junction denoted by a black dot,

\[
I_s = I_d + I_q \quad (3.1)
\]

Kirchhoff’s loop law on right loop,

\[
V_d = V_{bias} - I_q R_q \quad (3.2)
\]
Kirchhoff’s loop law on outer large loop,

\[ V_{bias} - V_{bd} - I_s R_s - I_q R_q = 0 \]  \hspace{1cm} (3.3)

Asymptotic condition for the capacitor: \( I_d \to 0 \) implies \( I_s \approx I_q \) (from Eq. 3.1)

Using \( I_s \approx I_q \) condition in Eq. 3.3 and solving for \( I_q \) gives,

\[ I_q \approx \frac{V_{bias} - V_{bd}}{R_s + R_q} \]

By substituting the value of \( I_q \) in Eq. 3.2, the potential difference across capacitor (in the asymptotic condition) is:

\[ V_d \approx V_{bias} - \frac{V_{bias} - V_{bd}}{1 + R_s/R_q} \]

For \( R_q \gg R_s \), \( V_d \to V_{bd} \), that large \( R_q \) compared to \( R_s \) quenches avalanche process. As \( V_d \) decreases, the electric field in the depletion region decreases, eventually becoming too weak to maintain Geiger - mode. Hence, the avalanche is quenched by \( R_q \) and the conceptual switch opens. At this instant, recovery process starts: \( C_d \) begins to charge from approximately \( V_{bd} \) to \( V_{bias} \) through \( R_q \) with the characteristic time constant \( t \approx R_q C_d \). This charging process is called recovery. At the end of the charging process, the APD is in the "ready" state. During the time of recovery, a GAPD is not fully ready to detect a new photoelectric event and if any output is generated during that period, it will have small amplitude depending on the remaining amount of charge on \( C_d \) that is available for a secondary discharge [14].
Figure 3.6: A theoretical positive pulse: the current measured across quenching resistor forms the positive pulse with current rising time determined by $R_s \times C_d$ and recovery time determined by $R_q \times C_d$. Since $R_q >> R_s$, the pulse rise time is very short in comparison to recovery time [14].

Fig. 3.6 shows a positive theoretical pulse generated from the discharging and recovery of an APD. The shape is generated by accounting for the current flowing through quenching resistor $R_q$ during discharge of capacitor $C_d$ via $R_s$ and charging $C_d$ via $R_q$ during recovery time. Thus, $R_s \times C_d$ determines the pulse rise time and $R_q \times C_d$ determines the pulse falling time i.e., recovery time of a GAPD. Since, $R_q >> R_s$ the pulse rises instantly in comparison to recovery time [14].

3.4 Some Characteristics of MPPC

3.4.1 Photon Detection Efficiency (PDE)

Photoelectrons are generated in the material by incident photons by quantum mechanical process and only a portion of those photons can generate photoelectrons. Quantum efficiency is defined as the ratio of the number of photo-generated $e-h$ pairs per unit time that produce an electrical signal to the number of incident photons on a photo-sensitive surface per unit
time. However, for devices like MPPCs, a quantity called photon detection efficiency (PDE) is used. It is defined as the product of quantum efficiency of the semiconductor material, pixel fill-factor - a ratio of pixel photosensitive area to total area and Geiger-mode avalanche probability. For Hamamatsu MPPC in 13360-**VE series, PDE values in the range 320 nm to 900 nm with maximum value of 40\% at wavelength of 450 nm, as shown in Fig. 3.7 [18].

Figure 3.7: Photon detection efficiency of Hamamatsu MPPC 13360-**VE series: PDE is maximum of 40\% around 450 nm and falls on both sides; and their spectral response is in the range 320 nm - 900 nm [18].

3.4.2 Dark Count Rate (DCR)

If a charge carrier (electron or hole), which triggers the avalanche in an APD of MPPC, is generated from thermal excitation, the resulting output pulse will be referred to as *dark*
count. In a normal operation, the bias voltage $V_{bias}$ on a MPPC is larger than the APD’s breakdown voltage $V_{bd}$ by a few volts; the difference $\Delta V = V_{bias} - V_{bd}$ is known as overvoltage. The DCR increases with both increasing temperature and increasing overvoltage.

The dark count in the MPPC is output pulse of one photoelectron (p.e.) level and it is very unlikely that dark counts at level $\geq 1$ p.e. are detected. The number of output pulses measured with no light incident on the MPPC and the threshold is set at 0.5 p.e. is called dark count (at 0.5 p.e. threshold). This implies that by setting a proper threshold level, the effects of dark counts can be virtually eliminated. Also, if the entry time of photons in the MPPC is known, setting a proper gate time also helps to reduce dark count rate \[16\].

### 3.4.3 Gain($M$)

Each pixel of MPPC independently works in Geiger-mode with an applied voltage, $V_{bias}$ a few volts above the breakdown voltage, $V_{bd}$. When a photoelectron is produced, it induces a Geiger avalanche. The avalanche is quenched by a resistor integral to each pixel. The output charge $Q$ from a single pixel is independent of the number of produced photoelectrons within the pixel, and can be written as $Q = C(V_{bias} - V_{bd})$ or $\Delta V = C$, where $C$ is capacitance of the pixel. Then, the gain of a Hamamatsu MPPC is, $M = Q/e$. The typical value of $M$ for Hamamatsu MPPC is in the range $\sim 10^5 - 10^7$.

### 3.5 Hamamatsu Specifications of MPPCs

Two types of MPPCs: 6 mm × 6 mm and 1.3 mm × 1.3 mm from Hamamatsu (shown in Fig. 3.8) will be used for the ADRIANO2 prototype. Large size MPPCs will be used with
Cerenkov radiators and smaller ones with scintillators. Specifications are given in the Table 3.1 (values of the variable parameters, typically at T = 25 °C):

Figure 3.8: Hamamatsu MPPCs of size: (left)6 mm×6 mm; (right) 1.3 mm×1.3 mm [14, 18]

Table 3.1: Specifications for 6 mm×6 mm and 1.3 mm×1.3 mm are given in the table; values of some variable parameters at T = 25 °C [18].

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>13360-6050VE</th>
<th>13360-1350PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective photosensitive area</td>
<td>6 mm×6 mm</td>
<td>1.3 mm×1.3 mm</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>50 µm</td>
<td>50 µm</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>14336</td>
<td>667</td>
</tr>
<tr>
<td>Package</td>
<td>surface mount type</td>
<td>surface mount type</td>
</tr>
<tr>
<td>Spectral response range</td>
<td>320 nm - 900 nm</td>
<td>320 nm - 900 nm</td>
</tr>
<tr>
<td>Peak Sensitivity wavelength</td>
<td>450 nm</td>
<td>450 nm</td>
</tr>
<tr>
<td>Dark count rate at 0.5 PE</td>
<td>2 MHz</td>
<td>90 KHz</td>
</tr>
</tbody>
</table>
CHAPTER 4
BUILDING ADRIANO2 PROTOTYPE COMPONENTS

For the ADRIANO2 prototype, it was planned to use eight identical glass tiles (10 cm × 10 cm × ∼ 1 cm) made of optically transparent lead-glass and eight identical scintillating plastic tiles (of cross-section 10 cm × 10 cm). Each glass tile should have four dimples in square arrangement of side length of 2 inch. The dimple should have appropriate size to fit in the photosensitive area of 6 mm × 6 mm Hamamatsu MPPC. However, plastic tiles would be thinner (thickness ≈ 4 mm) and dimples would fit 1.3 mm × 1.3 mm MPPCs. As Cerenkov photons are generated in much smaller number than scintillating photons, the glass tiles should be optimized for better reflection of the photons generated inside the tile and good transmittance through the dimples. To achieve latter requirements, the glass surfaces and dimples demanded optimal polishing and some optical coupling material in the dimples. All the development work regarding the preparation of Cerenkov radiators and scintillators are described in this chapter.

4.1 Cutting a Glass Block Into Tiles

Two rectangular lead-glass block of cross-section 10 cm × 10 cm, density of 3.56 g/cm³, refractive index $n_D > 1.8$ and length of about 55 cm were sliced into rectangular tiles. Cutting of glass block was done at the mond-saw laboratory in Geology Department. It is a big and stable saw, especially, used for cutting large rocks. Cooling is provided by oil bath as shown in Fig[4.1]. It produced a glass tile of reasonably smooth surface in about 50 minutes.
After each cut, the table is moved away from the saw-edge and glass-block is advanced towards the saw by the amount equal to thickness of the tile. Nine complete rotations of the handle advanced the block by 9.8 mm so all our tiles have thickness of 9.8 mm. The saw has auto power-off system after job is completed. The problem of chipping at the top corner at the end of slicing was avoided by gluing (with superglue) another thick strip of glass along the top edge, as shown in Fig. 4.1. Stack of glass tiles by cutting block of a glass at the mond-saw are shown in Fig. 4.2 (tiles with deep scratches were sliced using the saw at glass shop). The dimensions of the tiles obtained from the mond-saw are: 10 cm × 10 cm × 0.98 cm.

Figure 4.1: The mond-saw at Geology Lab: this large and heavy saw is used to slice the glass block to make tiles of required thickness.

4.2 Polishing Of Glass Tiles

As a first approach to polishing the glass surface, fire polish was tried on small size tiles over the range of temperature and time: starting from 480 °F to 910 °F and holding at different temperatures for different duration of time in a programmable heater. Fig 4.3 (left) shows the the appearance of tiles with increasing temperature. Below 700 °F, even heating
Figure 4.2: The mond-saw sliced stack of tiles: the tiles sliced by the saw has uniform finish but the transparency has lost; a few tiles showing marks are the tiles cut at glass shop.

for half an hour didn’t bring any remarkable change, however, some glass piece cracked pretty soon if it was not transferred to another heaters at lower temperatures. Above 750 °F, appearance of the surface started to change (sample 30)slightly. Sample 41, 43 are obtained by heating at about 870 °F for 10 minutes and above. Above 870 °F, the glass sample started to melt with in just 5 minutes. Even though transparency was returned at the high temperature but its surface was excessively melted and deformed. Thus, polishing by heating at lower temperature wasn’t successful, doing so at those high temperatures also demanded the study of any change in the properties of the glass before using this method for polishing the glass surface.

The tiles that came out of the saw, to aided eye, lost previous transparency and their surfaces might have different degree of irregularities at microscopic level. Thus, it required to examine the quality of the surface. For the indication purpose, a few tiles were polished using cerium oxide slurry and comparative quick measurement of the light output from the tiles without or without polishing was done using $\beta$ source at NICADD. These quick tests suggested that there was improvement in light yield with polished surface.
Figure 4.3: Polishing by heating: (left) shows samples heated from 480 °F - 910 °F with specimens 15, 16 being heated at or below 500 °F and 43, 45 being heated around 900 °F; (right) shows programmable heater used to heat the samples.

The set up, as shown in Fig. 4.4, was used to polish tiles with the slurry of cerium oxide in water. Some weight (∼ 250 g) was placed on the top of the tile to save the tile edges from cracking from frequent hitting against fixtures while rotating. Tiles were rotated by 90° every 15 minutes for uniform polish. Cerium oxide solution was added every 5-10 minutes on the pad so that there would be continuous supply of polishing grains.

It was observed that, the transparency in the most of the middle portion of the tile is returned in about 1.5 hours. However, it took long time to obtain same transparency all over the surface because tile was significantly large given the size of rotating pad so tile was kept close to the center of the wheel leaving behind more effective area of the wheel unused. I would recommend large polishing pads for this size glass tiles to use with the available large wheel. Polishing was even harder if the tile was not reasonably flat. All tiles were polished for about 5 hours (including both surfaces). The cerium oxide slurry shouldn’t be too thick or too thin: thick did not spread under the tile uniformly and too thin solution just flew away immediately.

It is the best strategy to have arrangement to spray the solution frequently but in small amount to have effective polishing and efficient use of the solution. Also the pad on the
wheel should be removed after \( \sim 6 \) tiles are polished. For our purpose, slurry of cerium oxide solution was prepared in a plastic bottle and squirted into the pad. The transparency of the glass was returned with this polishing, as shown in Fig. 4.5.

Figure 4.4: Setup for polishing the surface: the polishing pad is glued on rotating wheel and fixtures hold the tile in place. Cerium Oxide solution is sprayed on the pad while wheel rotates.

Figure 4.5: A polished tile with cerium oxide solution (left); a cleaned but unpolished tile (right).
4.3 Micro-Surface Analysis

Surface analysis of the polished and unpolished tiles was done at Department of Engineering, NIU with a microscope. Fig. 4.6 shows the representative 1 mm portion of the surface of unpolished tile, and irregularities within 1 mm width vary from 0 - 30 µm meter, however, most of the surface irregularities are within 3 µm. Fig. 4.7 shows the features of 10 mm surface of polished tile: deeper scratches are not removed and the tile surface is not very flat but minor scratches and debris are removed.

Figure 4.6: Unpolished tile under microscope: tile from the saw is scanned over 1 mm length at different places; graphs show that most irregularities are within 3 µm; pits formed during cutting are about 5 mm wide.

Moreover, surfaces study at microscopic level showed that slicing a glass block with the mond-saw created some pits on the surface of tiles of width ~5 mm and depth of (10 -15) µm, as shown in Fig. 4.8. While the polishing made the tile look transparent, but the deeper scratches and large irregularities (similar to pits) didn’t go away completely. Despite of all that, tiles were still polished only with cerium oxide, partially because the number of pits
Figure 4.7: Polished tile under microscope: polished tile is scanned over 10 mm length at different places; shows that polishing can’t remove large deep irregularities; reveal that surface is not completely flat.

Figure 4.8: Polished tile under microscope: scanning polished tile over 10 mm length reveals presence of large pits formed during cutting the tile; shows that polishing can’t remove big irregularities though transparency returned to naked eyes.
were a few and pits size were not bigger than 15 µm and partially because of unavailability of lapping tools to do polishing in steps.

4.4 Making The Dimples

The dimples on the tiles were planned that they will provide better placing of the MPPCs and better sandwiching of tiles and carrier boards together. In addition, they probably provide some uniformity in the signals generated inside the tile. The plan is to use 6 mm × 6 mm MPPC with its photosensitive area to be exactly completely inside the dimple. It required the 10 mm diameter diamond miller to mill a dimple of the depth 4 mm to have required opening on the surface. Fig. 4.9 shows small CNC (Computerized Numerical Control) machine used to make dimples on the glass tiles.

![Small CNC machine used to make dimples on the tiles.](image)

Figure 4.9: Small CNC machine used to make dimples on the tiles. The g-code running on the computer screen was first generated with C++ code and then fine tuned to work with correct spindle speed.

Initially, a C++ program is written to generate a sample of G-code and manipulated many times to use 10 mm miller. But, using 10 mm miller to make dimples in one shot was not successful. So, I started to work with 6 mm miller. While working very carefully with
the machine and tool (tens of editions of G-codes for feed rate and spindle speed were tried),
and I was successful to make 6 mm tool to work. The idea was to use smaller tool to make
smaller dimples so that probably 10 mm tool might successively widen the dimples. Then
10 mm miller was applied on already made small dimples, it worked better than pre-dimple
case but still broke a few tiles. Then, I revised G-codes several times for 8 mm miller, and
finally it worked. Both 6 mm and 8 mm millers can be operated at full spindle speed and
work is fully automated. With 8 mm tool, it took about 1 hour 30 minutes per dimple so,
it took 6 hours to have smaller dimples for one tile. Dimples with this diamond miller were
excellent using the optimized final version of G-code file. The finalized G-code files are in
the appendixes. One diamond ball only works for two tiles so miller should be changed after
making at most eight dimples. However, we can reduce the feed rate using on screen control
button offsetting for the withering diamonds in the miller after making a few dimples. Then
10 mm miller was used to widen the dimple to proper size but the code for 8 mm miller
didn’t work and it required further revisions. After many hit and trials of changing feed rate
and spindle speed, it was found that larger tool not only required revision in feed rate but
also variable spindle speed. It was found that the spindle rate should be kept to level 4 - 4.5
until depth of 0.1000 inch; it should be increased to level 5 until the depth of 0.1300; finally
to level 6-7 for depth of 0.1300 inch to 0.1600 inch. Large miller also should be replaced
after every two tiles and offsetting for withering tool should be considered by increasing
spindle speed by ∼ 20%. This CNC is not appropriate for milling glass with 10 mm milling
diamond, however, it can be used with smaller size millers. The very necessary cooling was
provided by submerging the glass tile in the water as shown in Fig. 4.9. There was a lot of
time and effort expended on this machine with the hope that the dimple making process will
be automated but 10 mm miller required change of spindle speed which is manual. Thus
making dimple with tool large than 8 mm is not completely autonomous and extremely time
consuming with this machine.
4.5 Polishing The Dimples

Several comparative light output tests were performed on tiles with or without polished dimples by using $\beta$ particle source at NICADD. The electronic circuit, as shown in Fig. 4.10, contained one Hamamatsu 6 mm $\times$ 6 mm MPPC on one of the dimples to readout the signal produced by $\beta$ particle on traversing through the tile.

Figure 4.10: Preliminary light output test: (left) beta source on the top of the MPPC inside a large dark box; (right) single 6 mm $\times$ 6 mm Hamamatsu MPPC used as readout for the signal generated inside the radiator.

Those tests strongly suggested that polished dimples yield at least three times more light than unpolished one. So, it became clear that the tiles should be polished. But, it was more difficult to polish dimples than surface for various reasons: the glass is so fragile that no hard substance can be used for polishing; soft material takes very long time for any effective polishing; fast spinning can not be applied because of heat dissipation problem of glass;immersing in water option is not available because diamond paste should be used for polishing; available cotton felts did not have the shape of the dimples so any other shape wouldn’t polish all portions of the dimple equally.

Cotton felts of different thickness and lengths were chosen for polishing and used with diamond paste of different grit size. Initially, same CNC machine was used for polishing, as
shown in Fig. 4.11 (left). Spindle speed was kept very slow for polishing to avoid cracking of dimples because of heat build-up and G-codes was written so that every 3-5 minutes tool would come out of dimple to allow addition of more diamond paste. This method was tried on some tiles, running the same code over many cycles but dimples were not polished good. Finally, this method was dropped.

After then, another slowly rotating motor is used for polishing, and its total weight was used as pressure while polishing, as shown in Fig. 4.11 (middle). It was more effective than CNC but it required manual lifting to add diamond paste. This can also crack dimples if water is not added frequently because of heat. So at later stage initial polishing was done with this slow rotating motor and final polishing was done with hand-held driller, Fig. 4.11 (right). Drill could be moved around the dimple and variable pressure could be applied with decreasing grit size diamond pastes. Manual polishing took about 3 hours on each tile to final polishing. The deep circular lines made by spinning diamond ball were tough to remove as much as it was to polish the very narrow bottom of the dimples. Fig. 4.12a and Fig. 4.12b show dimples before and after polishing respectively.

Figure 4.11: Left: first rounds of polishing of dimples using CNC machine with diamond paste and cotton felt; middle: polishing of dimple with heavy yet slowly rotating motor; right: final polishing of dimples on hard scratches and bottom of the dimples by handheld motor.
4.6 Optical Grease

Since the Cerenkov light is produced at intensity much lower than the scintillating light, scattering off the light that has arrived at the dimple is not desired. So, to provide the optical continuity from glass to photo-sensors of the MPPC, it is required to have the dimples filled with optically transparent material of refractive index closer to that of the glass. As the tiles are supposed to be used vertically, it should be viscous enough that grease won’t flow out of the dimples. Also, once the MPPC settles on the grease, the trapped air should be removed. The optical grease was made from powdered resin by dissolving it, in small amounts, in the solvent oil for months. Finally, some more resin was dissolved at an elevated temperature so that when the grease comes back to room temperature it would be optimally viscous. The dimples were filled with warm grease (at about 65 °C) and MPPCs were installed on it. The setup was kept in the vacuum for about 3 hours to expel the trapped air in the grease by the
process of installing sensors on the dimples. Fig. 4.13 shows a tile with dimples filled with the grease is kept inside vacuum at about 65 °C and pressure of 18 inch of Hg.

Figure 4.13: Glass tile with optical grease is kept inside the vacuum chamber at 65°C and pressure of 18 inch of Hg. By the combined effect of the heat and vacuum condition, trapped air inside the grease is popping out.

4.7 Making Paint and Spraying

The polished glass surfaces should be covered with the best reflective material possible so that the surfaces will bounce back the photons escaping out from the glass. To cover the surfaces of all the reflectors of actual detector would require a large amount of reflecting material. It also must have high reflectivity over the wide range of wavelengths. Therefore, we have been looking for the reflecting substances that are comparably cheap yet having high reflectivity coefficient over the wide spectral range.

$BaSO_4$ is a novel reflecting material towards our purpose that it has high diffuse reflectivity over a reasonable wavelength range and it is relatively cheaper. Therefore, $BaSO_4$ as reflector was investigated over months. It is commercially available in the white powder form. Due to its powdery form, it should be mixed with some binders before applying on the tile surface. Many different oil-based as well as water-based binders were tried for a long
period of time to incorporate as much amount of $BaSO_4$ as possible. It took significant
period of time to figure out the appropriate recipe to make $BaSO_4$ paint using different
binders. It also took long period of time to find an appropriate combination of the size of
nozzle of the spray gun, air-pressure, diluting liquid and the level of dilution to spray the
paint uniformly and efficiently. Finally, a spray gun with nozzle diameter of 1.2 mm worked
for all paints with air pressure in the range $35 - 40 \, kg/cm^2$. Specifics of the paints that we
worked with are given below.

![Figure 4.14: Two tumblers revolve around the bottles containing the mixture of barium sulf
ate powder and different kinds of binders to prepare the reflecting paint.](image)

**4.7.1 Oil-Based Barium Sulfate Paints**

Oil-based paints are durable compared to water-based paints and less vulnerable to mois-
ture. Moreover, it was thought that the $BaSO_4$ paint made with an oil-based binder might
have the reflectivity comparable to that of a water-based binder. Thus, initially, we tried to
make oil-based paint by dissolving resin pellets in solvent oil. It took a long period of time
to dissolve a reasonable amount of resin in the oil to make homogeneous binder. Then, it
took another one month to mix $\text{BaSO}_4$ of weight equal to the weight of the binder. In addition to that, significant period of time was invested to make the paint sprayable. Dilution with alcohol and acetone were also tried but by the time paint would be dilute enough for spraying, the resin will separate out. This sample didn’t work as intended.

After that, casting resin (oil-based binder) was used to dissolve $\text{BaSO}_4$ to make the paint. This resin comes in two parts: part A and part B. $\text{BaSO}_4$ was dissolved separately in part A and part B and two parts are only mixed together just before spraying as the mixture hardens immediately. The working ratio of $\text{BaSO}_4$ and this binder to make the paint and the appropriate ratio the weight of the paint and the alcohol (diluting agent) before spraying are given in the following section.

4.7.1.1 Barium Sulfate Paint in the Casting Resin Binder

Crystal-clear resin by Smooth-on, Inch. was used as binder to make a sample of $\text{BaSO}_4$ paint in oil-based binder. Casting resin part A and Part B were taken in the ratio of A:B = 10:9 in two separate bottles and the barium sulfate powder was dissolved in small amounts. Initially, the same amount (by weight) of $\text{BaSO}_4$ and the binder were added in a bottle and allowed to mix for about 10 hours in a rotating tumblers as shown in Fig. 4.14. After that, the $\text{BaSO}_4$ should be added in small increments and allowed to mix very well. Table 4.1 gives the weight the binders and the weights of $\text{BaSO}_4$ added in steps for two samples of $\text{BaSO}_4$ paint in binders A and B. The paint becomes ready for spraying in about 3 days and contains the $\text{BaSO}_4$ about two times the weight of the binder. The paint in ready state looks very viscous, homogeneous and hardly flows out of the bottle. Fig. 4.15 shows the containers of binders used to make paint and spray gun of 1.2 mm nozzle diameter used for spraying.
Table 4.1: Two samples illustrate the amount of Casting resin (type A and B) mixed separately with barium sulfate powder to prepare the oil-based paint; barium sulfate amounts are expanded to show how much was added in each step.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Resin A(g)</th>
<th>Barium Sulfate(g)</th>
<th>Resin B(g)</th>
<th>Barium Sulfate(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>40+5+5=50</td>
<td>36</td>
<td>40+10+5=55</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>40+5+5=50</td>
<td>36</td>
<td>40+10+3=53</td>
</tr>
</tbody>
</table>

After saturating amount of barium sulfate was dissolved, the paint was taken in another mixing bowl to prepare it for spraying. Some more barium sulfate was added while mixing Part A and Part B in the tumbler with little amount of alcohol. Thus, by the time the paint was sprayed, the weight of \( \text{BaSO}_4 \) in the paint exceeds two times the weight of the binder. Finally, more alcohol (propanol) was added for proper dilution and mixed for \(~5\) minutes and then the paint was filtered into the collection tank of spray gun. With a proper adjustment of air-pressure and nozzle opening, the paint was sprayed over the tile one layer at a time with a gap of at least 20 minutes between any two layers. However, after about five layers, the paint was allowed to dry for about 48 hours before adding another 5 layers. Table 4.2 gives five samples prepared for spraying casting resin based paint. Too dilute paint didn’t adhere to the surface and developed air bubbles and cracks. A few tiles including tiles tested at Fermilab Test Beam Facility (FTBF) were coated with this paint.
Table 4.2: Five samples in the table show the amount of part A and B of paints added with more barium sulfate paste. The dilution required for spraying is provided by propanol.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Paint (g) (10A:9B)</th>
<th>Barium sulfate paste (g)</th>
<th>Alcohol (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20 + 18</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>35 + 30</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>15 + 12</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>10 + 8</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>12 + 11</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>

4.7.2 Water-Based Barium Sulfate Paints

Initially, for a quick test, a few oil-based and water-based paints were prepared and their reflectivity were measured. The study showed that $\text{BaSO}_4$ paint with water-based binders had higher reflectivity than oil-based binders within the spectral range of interest. Thus, for second extensive work on $\text{BaSO}_4$ paint, more efforts were given to water-based binders. Three types of such binders: GAC-200, glazing medium and gloss medium - all acrylic medium, were thoroughly examined. It demanded many trials before finding a working recipe for making paint and spraying it.

Figure 4.16: Containers of the water-based binders used to make $\text{BaSO}_4$ paint.
Fig. 4.16 lists the containers of binders used to make water-based paints. To prepare a sample of paint, $BaSO_4$ is dissolved in a binder, until saturation, in small amounts. Initially, equal amount (by weight) of $BaSO_4$ and the binder were added in the bottle and allowed to tumble for about 10 hours. Subsequently, barium sulfate was added in small increments (5 g or 2.5 g) and allowed to mix well. Addition of some amount of distilled water mixed more $BaSO_4$ and helped in quick mixing of the components. However, addition of water required more time to dry the sprayed paint and had higher chances of cracks.

Then, small amount of paint was taken in another bowl to prepare it for spraying and propanol was added for necessary dilution. In case of GAC-200, it could not be sprayed by diluting with alcohol alone, so small amount of water was added in addition to alcohol. Meanwhile, taking advantage of water addition of water, small amount of barium sulfate paste (made in alcohol) was added and mixture was allowed to mix for about 5 minutes. Spray gun of 1.2 mm diameter was used to spray this paint at an air pressure up to 40 $kg/cm^2$.

Representative samples are given in Table 4.3 and Table 4.4 corresponding to preparing $BaSO_4$ paint GAC-200 binder and diluting the paint for spraying.

Table 4.3: Two samples illustrate the amount of GAC-200 binder mixed with barium sulfate; total barium sulfate amount is expanded to show it was added in steps.

<table>
<thead>
<tr>
<th>Sample</th>
<th>GAC-200(g)</th>
<th>Water(g)</th>
<th>Barium sulfate(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34</td>
<td>18</td>
<td>30+20+10+5+5+5=75</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>10</td>
<td>20+15+10+5=50</td>
</tr>
</tbody>
</table>

Table 4.4: Table shows the amount of paint, distilled water and propanol mixed together before spraying of the paint on GAC-200.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Paint(g)</th>
<th>Water(g)</th>
<th>Alcohol(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>2</td>
<td>12</td>
</tr>
</tbody>
</table>
BaSO\textsubscript{4} was added similarly in glazing and gloss-varnish binders (acrylic binders) to make corresponding paints. Dilution with water before spraying was not necessary for these two binders and these paints were easier to spray compared to BaSO\textsubscript{4} paint in GAC-200. Representative samples are given in Table 4.5, Table 4.6, Table 4.7 and Table 4.8 corresponding to mixing of barium sulfate in glazing and gloss-varnish binders and diluting the paints before spraying.

Table 4.5: Two samples illustrate amount of Glazing medium binder mixed with barium sulfate powder; barium sulfate amount is expanded to show it was added in steps.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Glazing medium(g)</th>
<th>Water(g)</th>
<th>Barium sulfate(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>12</td>
<td>25+15+10+5+5=60</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>14</td>
<td>20+20+10+10+5+5=70</td>
</tr>
</tbody>
</table>

Table 4.6: Three samples illustrate the amount of paint, distilled water and propanol alcohol mixed together before spraying of the paint.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Paint(g)</th>
<th>Barium sulfate paste(g)</th>
<th>Alcohol(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>5</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 4.7: Two samples illustrate amount of Gloss-Varnish binder mixed barium sulfate powder; total barium sulfate amount is expanded to show it was added in steps.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Gloss-Varnish(g)</th>
<th>Water(g)</th>
<th>Barium sulfate(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>18</td>
<td>40+20+20+10+10=100</td>
</tr>
</tbody>
</table>

Fig. 4.17 and Fig. 4.18 show glass tiles painted with 20 layers of barium sulfate paint made in four types of binders: Casting resin, GAC-200, Glazing, Gloss-Varnish binders respectively.
Figure 4.17: (a) A glass tile sprayed with barium sulfate paint on casting resin binder (oil-based); (b) A glass tile sprayed with barium sulfate paint GAC-200 (water-based)

Figure 4.18: (a) A glass tile sprayed with barium sulfate paint on Glazing medium binder (water-based); (b) A glass tile sprayed with barium sulfate paint Gloss-Varnish binder (water-based)
Table 4.8: Two samples illustrate the amount of paint, distilled water and propanol alcohol mixed together before spraying of the paint.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Paint (g)</th>
<th>Barium Sulfate paste (g)</th>
<th>Alcohol (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>6</td>
<td>11</td>
</tr>
</tbody>
</table>

4.8 Cerenkov Radiators for the Test Beam

Many lead-glass Cerenkov radiators of dimensions 10 cm × 10 cm × 0.98 cm were prepared at Northern Illinois University (NIU) and three of them were tested at a test beam. For reflection of light from the surface, one of them was coated with $BaSO_4$ paint prepared with oil based casting resin (acrylic) binder and remaining two were wrapped in ESR-2000 foils. One $BaSO_4$ paint coated tile and one ESR-wrapped tile had their dimple filled with the optical grease. Out of four dimples, only three had MPPCs with their own small carrier boards. Out of the three MPPCs, two MPPCs were of size 6 mm × 6 mm and third MPPC was of size 3.5 mm × 3.5 mm. The MPPCs on carrier boards were mounted on the dimples such that photo-sensitive area is just inside the optical grease. The optical grease was thick enough so that it won’t flow out of the dimple below 45°C.

Fig. 4.19 shows three Cerenkov radiators taken to Fermilab Test Beam Facility (FTBF) in July 2019 for test and measurement.

4.9 Progress towards ADRIANO2 Prototype

The work towards the building of ADRIANO2 prototype is near to the completion. Many of its components are ready. The following brief summary gives present status of the prototype to be tested at Fermilab test beam in December 2019.
Figure 4.19: Three Cerenkov tested at FTBF. First two glass tiles are coated with $BaSO_4$ paint (in casting resin binder) and last glass tile is wrapped in ESR-2000 for reflecting the light from the surface. The dimples are filled with optical grease for optical continuity.

**Cosmic Ray Setup.** Cosmic ray stand has been setup in the lab at NIU and the data acquisition systems is in working condition. The prototype cells will be tested at this setup before taking the ADRIANO2 to the test beam.

**Cerenkov Radiators.** At least eight glass tiles are ready and the ESR-2000 wraps for the shape and size of the tiles have already been cut. Next, the optical grease will be put on the dimples before wrapping with ESR-2000. The MPPCs of size $6 \text{ mm} \times 6 \text{ mm}$ will be installed on the top of the dimples. Fig. 4.20 shows some of polished Cerenkov radiators for the ADRIANO2 prototype.

**Scintillators.** For scintillation, 10 plastic tiles of dimensions $\approx 0.4 \text{ cm} \times 10 \text{ cm} \times 10 \text{ cm}$ are cut and four dimples are milled on each tile. Four dimples on a tile form a square of side length 2 inch. Eight plastic tiles will be needed for the ADRIANO2 prototype. The scintillator tiles are thinner and dimples milled on it are appropriate for $1.3 \text{ mm} \times 1.3 \text{ mm}$ MPPCs. The scintillator tiles, shown in Fig. 4.11 are ready for wrapping with ESR-2000.

**Electronic Circuits.** The electronic circuits are already printed and to be dispatched for installing MPPCs on them at Fermilab. Fig. 4.22a shows the sample carrier board which was prepared in June and tested to work fine, which contains four $6 \text{ mm} \times 6 \text{ mm}$ MPPCs and Fig. 4.22b shows recently printed stack of circuit boards.
Figure 4.20: Lead-glass tiles: some of the tiles are polished completely and some them require final manual polishing of dimples.

Figure 4.21: (Left) The scintillator tile showing four small dimples milled on it (for 1.3 mm × 1.3 mm MPPCs); (right) the stack of scintillator tiles, ready for wrapping with ESR-2000 reflector.
4.10 Reflectivity Measurement

Fourteen samples were prepared for measurement of their reflectivity. The total reflectivity of all those samples was measured with Prof. Evgueni’s spectrometer at Chemistry department.

Out of 14 samples, two were ESR-2000 foils taped on glass surface: first ESR sample with its reflecting surface freshly exposed and second with its reflecting surface pre-exposed a day before. Out of 12 other samples, 9 samples were $BaSO_4$ paint (water-based) sprayed on the glass tiles and 3 samples were $BaSO_4$ paint (oil-based paint) sprayed on the glass tiles.
For each kind of \( \text{BaSO}_4 \) paint, 3 tiles consisting of 10, 20, 30 layers were prepared. Fig. 4.23 shows three samples of thickness 10, 20 and 30 layers (left to right) after paint has dried.

Total reflectivity\((%R)\) of all samples relative to the standard reflector for different types of paints are presented below.

### 4.10.1 Reflectivity of \( \text{BaSO}_4 \) Paint in Casting Resin Binder

The total reflectivity of three samples of thickness of 10, 20, 30 layers of barium sulfate paint in casting resin binder is shown in Fig. 4.24. Reflectivity of the paint increases with increasing number of layers but it remains almost constant for range of wavelength 420-750 nm. Below 420 nm, reflectivity of all samples falls sharply and gets as low as 10\% in between 320 nm and 370 nm. There is some increase (upto 30\%) near wavelength of 270 nm, however, the MPPCs photon detection efficiency is very low in that region of wavelength.

![Reflectivity of barium sulfate paints (in casting resin binder) of thickness 10, 20, 30 layers.](image)

Figure 4.24: Reflectivity of barium sulfate paints (in casting resin binder) of thickness 10, 20, 30 layers.
4.10.2 Reflectivity of $BaSO_4$ Paint in GAC-200 Binder

The total reflectivity of three samples of thickness of 10, 20, 30 layers of barium sulfate paint in GAC-200 binder is shown in Fig. 4.25. Reflectivity of the paint increases only slightly (about 1%) with increase in thickness of the paint in the wavelength range of 390-750 nm. So GAC-200 based paint has higher reflectivity than casting resin based paint over the same spectral range. Below wavelength of 390 nm, the reflectivity of all samples starts to fall but not as rapidly as oil-based paints. It is worth noting that the reflectivity remains above 60% for the wavelengths as low as 270 nm.

![Reflectivity vs Wavelength](image)

Figure 4.25: Reflectivity of barium sulfate paints (in GAC-200 binder) of thickness 10, 20, 30 layers.
4.10.3 Reflectivity of $\text{BaSO}_4$ Paint in Glazing Binder

The total reflectivity of three samples of thickness of 10, 20, 30 layers of barium sulfate paint in Glazing binder is shown in Fig. 4.26. Reflectivity of the paint is almost same for all three samples ($\approx 98\%$) and remains constant in the wavelength range 390-750 nm. Below wavelength of 390 nm, the reflectivity of all samples starts to fall rapidly and reaches to $\approx 40\%$ at 270 nm and continuously falls with further smaller wavelengths.

![Reflectivity vs Wavelength](image)

Figure 4.26: Reflectivity of barium sulfate paints (in Glazing acrylic binder) of thickness 10, 20, 30 layer.

4.10.4 Reflectivity of $\text{BaSO}_4$ Paint in Gloss-Varnish Binder

The total reflectivity of three samples of thickness of 10, 20, 30 layer of barium sulfate paint in Gloss-Varnish binder is shown in Fig. 4.27. Reflectivity of the paint is almost same for all three samples ($\approx 98\%$) and remains constant in the wavelength range 390-750 nm.
Below wavelength of 390 nm, the reflectivity all samples starts to fall rapidly and behaves almost same as the $BaSO_4$ paint Glazing binder.

![Reflectivity vs Wavelength](image)

Figure 4.27: Reflectivity of barium sulfate paints (in Gloss-Varnish acrylic binder) of thickness 10, 20, 30 layers.

### 4.10.5 Reflectivity of ESR-2000 (fresh & pre-exposed) Foils

The total reflectivity of two samples of ESR-2000 foils were measured. Fig. 4.28 shows reflectivity of two ESR-2000 samples: one with plastic coating from the reflecting surface is freshly removed and other pre-exposed a day before. Reflectivity of the foils are above 100% in the wavelength range 400 - 750 nm. However, it falls rapidly below 400 nm and goes as low as 30% at wavelength $\sim 370$ nm. Both samples have very small reflectivity in the wavelength range of 320 - 370 nm, which is the spectral range for which MPPCs have minimum photon detection efficiency (PDE).
Figure 4.28: Total reflectivity of ESR-2000 (fresh and pre-exposed) foils.

Figure 4.29: Total reflectivity of different types of materials considered for using as reflector for ADRIANO2 radiators.
Fig. 4.29 gives comparison of total reflectivity across all types of reflectors. For wavelength range of 400 - 750 nm ESR-2000 has the highest reflectivity of all five reflectors and barium sulfate paint in casting resin binder has the lowest. Below ∼ 390 nm, reflectivity falls with decreasing wavelength. It is worth noting that GAC-200 performs best in the range of wavelength 250 nm - 370 nm.

In conclusion, analyzing the total reflectivity graphs of all samples across the various thickness and across all types of reflectors, it can be said that oil-based paints in casting resin binder has the lowest reflectivity over the spectrum of interest. Glazing, Gloss and GAC-200 have about same reflectivity (∼ 98%) over the wavelength range of 390 - 750 nm but, GAC-200 performs better at lower wavelength because its reflectivity does not fall as sharply as it does for others. ESR has the highest reflectivity of all but it falls below wavelength 390 nm, making it less efficient for ultraviolet lights. Hence, for reflecting the photons within the wavelength range of 390 - 750 nm, any of last four reflectors could be used, but below 390 nm, GAC-200 based paint works best.
CHAPTER 5

TEST BEAM SETUP

5.1 Data Acquisition System

The data acquisition system used for collection of data at Fermilab Test Beam Facility (FTBF) involves many modules. This system consists of a DRS4 waveform sampling storage module, an ADC analog-to-digital conversion module, a FPGA data control and processing module and other modules. The DRS4 (Domino Ring Sampler) module samples the waveform of detectors sequentially, and converts the waveform amplitudes into the sampling charges. The ADC module digitizes the sampling charges and the FPGA module converts digital waveform information into binary files and uploads them to PC for off-line analysis. The detector signals are directly acquired by the DRS4 waveform sampling systems and the coincidence mode of the system can achieve the coincidence of the time signals of two photodetectors. The principle of coincidence mode is that, high levels are generated. Two high levels are sent into the FPGA for "and" calculation. If two events satisfy "and" calculation, they are a pair of coincidence events, and the system is set to the coincidence mode. The signals of detector are sampled with 1024 cells by DRS4 waveform sampling system [19].

5.2 Experimental Setup

Several Cerenkov radiators were prepared at Northern Illinois University. Out of which three were tested at Fermilab Test-Beam Facility (FTBF) in July 1, 2019 through July 5,
2019. It was planned to measure the light output from three radiators with some differences: one was ESR-2000 wrapped and optical grease inside the dimples; other was coated with the $BaSO_4$ paint and optical grease inside the dimples and the last one was ESR-2000 wrapped but without optical grease. For readout, two Hamamatsu MPPCs of size 6 mm $\times$ 6 mm and third one of 3.5 mm $\times$ 3.5 mm was placed on the dimples such that the photosensitive area is just inside the optical grease. Two big MPPCs were labeled CH-0 and CH-1 and small MPPC was labeled CH-2. Fig. 5.1 shows $BaSO_4$ coated and ESR-2000 wrapped and instrumented Cerenkov radiators before installing them in a beamline for the test. Before placing them in the beamline, the radiators were placed inside the light-tight box, called darkbox. Fig. 5.2 shows a Cerenkov radiator placed inside the darkbox along with input/output terminals for connecting cables from inside and outside.

Figure 5.1: Cerenkov radiators tested at FTBF: (left) Barium Sulfate reflector coated glass tile ready for test; (right) ESR-2000 wrapped glass tile ready for test.

Then, a white coated Cerenkov radiator was placed inside the dark-box and tile was connected to power supplies and DRS4. Fig. 5.2 (right) shows the DRS4 used during the test beam. The DRS4 device reads the ADC values provided by ADC buffers connected to the MPPCs and relays to the computer via Ethernet cable. Fig. 5.2 (left) shows white coated radiator inside darkbox facing beamline and across the beam-line, in front of the darkbox, a square shaped silicon strip detector of scintillating type. This silicon tracker can be seen in
front of the box in Fig. 5.2 (left). Its dimensions were 36 mm × 36 mm and it served as a particle tracker.

![Image of the box](image1.png)

**Figure 5.2**: (Left) white coated radiator is placed in the darkbox and all cables are connected; (right) DRS4 used used for data acquisition

The motorized platform was elevated to the height that the beam will be on the tile and could be moved to the desired \((x, y)\) position. The motor was set to move one inch for input of 100 k, \(k = 1000\) steps in \(+x\) or \(+y\) direction from its home position. Moreover, its motion can be monitored in the computer from the control room. Fig. 5.3 shows the darkbox connected to motorized platform and a graph paper on the face of the darkbox is outlining the reference position of glass tile as well the center of the beam in the home position of the motor. The position information contained in the graph paper is used to estimate the coordinates of the center of MPPCs for analysis of the signals for different runs of events.

Fig. 5.4 shows all power-supplies providing power to silicon tracker as well as photosensors on the tile. Common operating voltage of 54.5 V was applied to two 6 mm×6 mm and separate 41 V was applied to 3.5 mm×3.5 mm MPPPCs for proper biasing of the readouts for collection of photons that will be generated inside the glass tile when an energetic charge particle will arrive during each spill along the beamline.
Figure 5.3: The darkbox is fixed to the platform that can be moved by computerized motor. The graph paper on the side of the dark box gives outline of the radiator and center of the silicon tracker, and this information is crucial for finding coordinates of the MPPCs when box is displaced to different positions.

Figure 5.4: (Left) Shows all the power supplies used to provide operating voltage for three channels in the radiators, the silicon tracker; (right) the data acquisition software running on the pc with control buttons to start or pause or stop the data taking and the two blue distributions are showing the shape of the beam coming along the beamline.
Figure 5.5: (a)(left) Two phototubes facing the beamline that determine the coincidence; (a)(right) Nim+ trigger that sends in the trigger information; (b) Root TTree, named drsTree is showing all its branches and leaves of .root file for run563. There are many ntuples containing information about tracks, samples, hits and ADCs for signals for customized analysis of the run.

Triggering was provided by Nim+ trigger generator and coincidence was determined by two parallel phototubes situated behind the darkbox and facing the beamline as shown in Fig. 5.5a. These two devices facilitates the collection of manageable and useful set of data.

### 5.3 Data Collection and Processing

The data acquisition software running on a pc in the control room allows to control the collection of data. When the beam starts to flow along the beamline, beam profile can be seen on the visualizer tab of DAQ software and master control room (MCR) should be called for any beam adjustment or change. The data collection starts 25 seconds before the next
spill arrives and the acquisition continues until sufficient number of events are registered. The process can be repeated to register another run of events. Once the run is started and beam is going through the radiator, all the modules of data acquisition system are started.

For any analysis of the data based on the ROOT analysis framework, acquired raw data from various devices is processed. So several bash scripts were run to compile data obtained from DRS4 and tracker to produce .root output file. The ROOT TTree, Fig. 5.5b shows that the DRS4 has scanned 1024 ADC values from MPPC for each event, corresponding to each 1024 samples stored in the array (_ns[1024]) and ADC values for 4 channels are stored in double array, _ch[4][1024]. The ADC values for a channel plotted against all samples produces the waveform for any event for a given run.
CHAPTER 6
ANALYSIS

In this chapter, analysis of Run 563 is presented. For this run, protons of 120 GeV energy with intensity $\sim 50,000$ protons per spill (1 spill $\sim 5-7$ s) were impinging on Cerenkov radiator-wrapped in ESR-2000 and its dimples filled with optical grease. Fig. 6.1 shows the configuration of the radiator placed in the beamline. The large blue square represents the glass tile with three channels CH-0, CH-1 and CH-2 that contain MPPCs of $6 \, \text{mm} \times 6 \, \text{mm}$, $6 \, \text{mm} \times 6 \, \text{mm}$ and $3.5 \, \text{mm} \times 3.5 \, \text{mm}$ respectively. The diagram also shows the relative positioning of the tile, tracker, readouts and beam for the given run. It can be seen that CH-2 MPPC is within silicon tracker (dotted square at bottom-left). The coordinates of the center of three MPPCs are: CH-2 (18 mm, 9.6 mm), CH-1(18 mm, 60.4 mm) and CH-0(68.8 mm, 60.4 mm) as measured from the frame of silicon tracker (0,0). This run has 6053 events with well-defined tracks corresponding to one or more particle hits on the sensors of the tracker.

6.1 Calibration

MPPCs produce electric signals of different magnitudes when they receive Cerenkov photons generated inside the radiators and those signals can be converted to integer analog-to-digital(ADC) values. Signal outputs taken from anode of APDs form negative pulses and the signal pulses were negative in our measurement. In the absence of beam, the difference between average noise and average amplitude of the majority of signals gives the
conversion factor, also called ADC value for 1 photoelectron. This is known as calibration of MPPC. And the factor is used as scaling factor to convert any signal amplitude to number of photoelectrons (PEs). 'xx.root' file corresponding to Run 563 with 7975 events is used as input file in all C++/ROOT scripts for analysis.

6.1.1 Pedestal for CH-2 MPPC

Using C++/ROOT scripts, mean noise level for MPPC at CH-2, also known as pedestal value, is obtained from all ADC values when there is no beam. A pedestal accounts for residual voltage in the electronics, so it is present even if the devices are not receiving any light. To obtain mean noise value, all ADC values corresponding to 500 samples (samples 0-499) before non-trigger region for each event are filled in a histogram. Then, the Gaussian
function is fitted to the tallest Gaussian peak representing dark noise of the MPPC, and the mean value obtained from the fit provides the pedestal for the CH-2 MPPC.

Figure 6.2: Pedestal for CH-2: ADC values stored against samples 0-499 are filled in the histogram and Gaussian function fitted at the tallest peak gives mean noise level.

500 ADC values for each event are filled in the the histogram and most of them correspond to the fluctuation in the electronic noise. The tallest peak on right of the histogram represents the distribution of dark noise. Since fluctuation in noise is random, the peak for noise is bell shaped. The Gaussian function fitted to the noise peak give the pedestal of 32960 ADC, for 3.5 mm $\times$ 3.5 mm MPPC, as shown in Fig. 6.2

### 6.1.2 1 PE to ADC Factor for CH-2 MPPC

Since the signal pulses from our MPPCs are negative, the ADC values corresponding to the background noise are higher than that for any signal generated in the MPPCs. There are some signals from thermal excitation even in the absence of beam, and such signals are not generally larger than signal generated by one photoelectron(1PE). The average amplitude
corresponding to 1PE signals is required to convert the signals produced by the Cerenkov photons into equivalent number of photoelectrons. Using C++/ROOT script, the minimum of ADC values recorded by the DRS4 for each event in non-trigger region is filled in a histogram. This implies, for each event, a minimum of 500 ADC values (stored in 500 samples (0-499)) is filled in a histogram and the histogram as shown in Fig. 6.3 is produced. In the histogram a Gaussian is fitted on a peak that corresponds to minimum signals produced in CH-2 MPPC, called 1 PE signals by the thermal excitation or by the photons present in the darkbox, which is not perfectly light-tight. The peak on the right of 1 PE peak corresponds to the minimum of electronic noise fluctuations.

Figure 6.3: Histogram to find 1PE ADC for CH-2 MPPC: 1PE signals correspond to the first Gaussian distribution on the left of tallest peak, which being minimum of electronic noise fluctuations.

From Fig. 6.3, 1 PE ADC value obtained from the Gaussian fit is 32570 ADC values. For CH-2, ADC to PE factor = pedestal – 1 PE ADC value = 32960 - 32570 = 390 ADC/PE.
6.1.3 Pedestal for CH-1 MPPC

Similar procedure, as used above for CH-2, is used to determine the pedestal for MPPC at CH-1. The Gaussian function fitted to the tallest noise peak provides fitted value of 33000 ADC for pedestal of 6 mm × 6 mm MPPC, as shown in Fig. 6.4.

Figure 6.4: Pedestal for CH-1: ADC values stored in samples 0-499 of ADC values are filled in a histogram; a Gaussian function is fitted on the tallest bell shaped distribution; the mean of Gaussian gives the mean noise level.

6.1.4 1 PE to ADC Factor for CH-1 MPPC

Similar procedure that used for CH-2 can’t resolve 1 PE peak for CH-1 MPPC, as shown in Fig. 6.5. Analyzing the waveforms corresponding to CH-1 MPPC reveal that there is significant shift of mean noise level for significantly large number events. Thus, to calibrate CH-1, many waveforms were selected to estimate the 1 PE signal for 6 mm × 6 mm MPPC
at CH-1. Fig. 6.6 shows two such waveforms used to determine the ADC to 1 PE factor for CH-1 MPPC and the factor is 145 ADC/PE. It can be clearly seen from waveforms that some of the noise spikes are also of same height as the amplitude of the signal which spoil the resolution of 1 PE peak from the background.

Figure 6.5: Histogram shows the distribution of the minimum of ADC values of each event for 6 mm × 6 mm MPPC at CH-1. The 1 PE signal distribution is not resolved from the background.

Figure 6.6: CH-1 MPPC calibration waveform: (left) waveform for event-12 and (right) waveform for event-118 are representative waveform used to represent 1PE signal and their height is almost 145 ADC.
6.2 Some Representative Waveforms

For run 563, the 120 GeV protons were impinged the Cerenkov radiator. By the passage of protons, many Cerenkov photons must have been produced inside the radiator and eventually a fraction of them might reach the MPPCs at the dimples. In response to a collection of photons, the MPPCs generated electric pulses of various sizes. In the Fig. 6.7 through Fig. 6.9, some of the representative waveform are presented for three channels. Fig. 6.9 (left) shows the shifting of the mean noise level in significantly large number of waveforms for CH-1 and CH-0 MPCCs.
Figure 6.9: CH-0 Some waveform in trigger region: (a) waveform for event-335 shows problem with many of waveform that baseline shits; (b) waveform for event-1191 has large amplitude; (c) waveform for event-1225 has moderate amplitude

6.3 Light Output from CH-2

6.3.1 Comparison of Non-trigger and Trigger Region Signals

The pedestal of CH-2 MPPC is 32960 ADC and it is shifted to origin. Then, amplitudes of all signals are converted to equivalent number of photoelectrons by using PE to ADC conversion factor of 1PE = 390 ADC. For each event, 1024 ADC values (samples) are read from MPPC and first 500 values correspond to non-trigger values and after values after 520 correspond to trigger values. For non-trigger region, all the signals within the first 500 samples and for trigger region, only the signals within the range of 520 - 560 samples are converted into equivalent number of photoelectrons. The narrow cut is applied for the trigger region to avoid afterpulses and pulses due to a large numer of hits.
Figure 6.10: Background distribution (left): most of the events are either zero or 1 PE and occasional large amplitude pulses; beam ON signal distribution (right): many events with PEs greater than 2 PEs

Fig. 6.10 shows two histograms corresponding to distribution of PEs in non-trigger (beam off) and trigger region (beam on). Clearly, the distribution of light yield penetrates into higher PE region than the background. However, there are very few large signals above 40 PEs. Since, Cerenkov light generation is much less in intensity than scintillation, the y-axis is set in log scale. For 3.5 mm $\times$ 3.5 mm MPPC, there are about 13% events out of total of 6053 well-defined events that produced signals greater than 5 PE.

6.3.2 Light Yield Degradation with Distance for CH-2

The size of the radiator (100 mm $\times$ 100 mm) is about three times the size of tracker (35 cm $\times$ 35 cm) and effective size of the beam is smaller than the tracker. To utilize this physical situation, the study of the average amount of light recorded by a particular MPPC as a function of the position and the distribution of the particle tracks is devised. Since, only CH-2 is properly calibrated, such a two dimensional study is only presented for this channel.
As shown in Fig. 6.11 (right), six rings of increasing radii, each of width 5 mm, are centered on CH-2 MPPC.

![Image: Track distribution](image)

Figure 6.11: Track distribution: the distribution of particle tracks relative to tile, channels and tracker (left); track distributions in 5 mm wide rings at progressively increasing distances around CH-2.

Some of the photons detected by the MPPC at CH-2 could have been generated within those 5 mm wide rings. The corresponding signals are converted to equivalent number of photoelectrons and filled in a histograms using a C++/ROOT script. The histogram thus obtained gives the distribution of PEs that correspond to the photons generated due to the single particle hits in those thin rings. As the histogram represents the number of PEs recorded at CH-2, a Poisson probability distribution best suits the distribution. Therefore, a Poisson function is fitted to the histogram. The mean of Poisson distribution gives the average number of PEs detected at CH-2 because of particle hits in a particular ring around CH-2.

The histograms shown in Fig. 6.12 show that there are more tracks in 5-10 mm disc than those in 0-5 mm ring because both rings are within the Gaussian center of the beam but area of 5-10 mm ring is three times larger than the area of the smaller disc. Meanwhile, average number of PEs from smaller area is $3.7 \pm 0.2$ and larger area is $2.9 \pm 0.1$. The number of PEs from closer region is 0.8 PE more than that from the farther region.
Figure 6.12: PE distribution from 5 mm wide slices: Poisson distribution function is fitted to obtain average PE contribution of the rings at CH-2 (a) by 0-5 mm ring; (b) by 5-10 mm ring.

Figure 6.13: PE distribution from mm wide slices: Poisson distribution function is fitted to obtain average PE contribution of the rings at CH-2 (a) by 10-15 mm ring; (b) by 15-20 mm ring.
Figure 6.14: PE distribution from 5 mm wide slices: Poisson distribution function is fitted to obtain average PE contribution of the rings at CH-2 (a) by 20-25 mm ring, (b) by 25-30 mm ring.

Fig. 6.13 shows fitting of Poisson distribution functions to the histograms that correspond to 10-15 mm and 15-20 mm rings. There are less number of tracks in the outer ring than inner ring, however, outer ring is 1.4 times the area of inner ring. It is because the density of tracks is higher in inner ring. Average number of PEs from closer ring is 2.2±0.1 and that from farther ring is 1.3±0.1. The number of PEs from closer region is 0.9 PE more than that from the farther region.

As shown in Fig. 6.14, same procedure is followed as in previous two cases to the histograms corresponding to 20-25 mm and 25-30 mm rings. Area of larger ring is 1.2 times that of inner ring but the number of tracks are less in the outer ring due to single hit. Because of the Gaussian nature of the beam, the density of tracks falls further as the distance from the center of the beam increases. Average number of PEs from closer ring is 1.1±0.1 and that from farther ring is 1.1±0.2. The number of PEs are almost equal but error in mean value is two for larger ring than that for smaller ring. Since, the lead-glass is very dispersive medium
so that absorption of light strongly depends upon the wavelength of the light. Therefore, average light yield doesn’t fall as rapidly for longer distances as it did at shorter distances.

### 6.3.3 Average PE Yield vs Distance for CH-2

![Ch2:avg.PE vs distance](image)

Figure 6.15: Degradation of Average PE measured at CH-2: The average PE measured at CH-2 from 5 mm slices progressively away from MPPC; an negative exponential function (red curve) with constant slope is fitted.

The distance of the rings from their center versus the average PE measured at CH-2 from corresponding rings is plotted in the Fig. 6.15. The negative exponential function:

\[
f(x) = A \exp(-\mu x)
\]

, where \( A = 4.5 \pm 0.2 \) PE and \( \mu = 0.06 \pm 0.004 \) per mm is fitted. It shows a significant reduction in the intensity of light with distance in the glass. The reduction of light could be more complex than just constant slope exponential because of the beam center was very close
to the center of CH-2 and also the dependence of absorption of light in lead-glass depends on the wavelength of the light generated in the glass. This correlation requires analysis based on wavelength as well because of the fact that this glass is highly dispersive medium.

6.4 Light Output from CH-1

The pedestal value for CH-1 is 33000 ADC values and ADC to 1PE conversion factor is 145 ADC values (section 6.1.3-4). For analysis of light yield in 6 mm×6 mm MPPC at CH-1, again the pedestal is shifted to zero level and resulting amplitudes are converted to the equivalent number of PEs by using the conversion factor of 1 PE = 145 ADC values. The tracker and the beam are relatively far away from CH-1 in contrast to the MPPC at CH-2.

6.4.1 Comparison of Non-trigger and Trigger Region Signals

Clearly, there is difference in the distribution of PEs in the non-trigger and trigger regions. There are many events that have large PE yield in comparison to background as shown in Fig. 6.16. There are only very few large signals above 100 PEs, so PE range for trigger region is cutoff at 100 PEs. There are about 32% events with PEs greater than 5 PE, however, there are not many events with signals greater than 40 PEs. This is partially because Cerenkov light intensity is low and partially because CH-1 is far away from the beam.
6.5 Comparison of CH-1 and CH-2

CH-1 has a MPPC, about three times larger photosensitive area than MPPC at CH-2 so it is expected to have more light yield than the smaller one. But, the two MPPCs are subjected to different conditions: all the specifications are only available larger MPPC; CH-1 couldn’t be calibrated properly; CH-2 is closer to the tracker than CH-1. Consequently, there are multiple variables that make the straightforward comparison difficult. If MPPCs at CH-1 and CH-2 were properly calibrated, we expect average number of PEs from MPPC at CH-1 to be three times that of MPPC at CH-2 from the consideration of the ratio of their photosensitive areas (36/12.25 \(\sim\)3).

The background distribution for CH-1 and CH-2, as shown in the Fig. 6.17, gives the average background signal for CH-1 is 1.03 PE and CH-2 is 0.425. That is, CH-1 background is about 2.7 times that of CH-2, lower than that expected from the ratio the their photosensitive areas.
Figure 6.17: CH-1 background distribution (left): most of events are 0 and 1 and 2 PE events, so average PE yield is 1.03; CH-2 background distribution (right): most of events are 0 and 1 PE events, so average PE yield is .04.

Figure 6.18: CH-1 & CH-2 distribution of signal when beam is on. PEs distribution is shown for 0-60 PE for both channel. Distribution for CH-1 (left) has more events in 0-10 PEs than that for CH-2 (right) and average PE for CH-1 is still greater than CH-2 despite of it being closer (hence many large amplitude signals)
Fig. 6.18 presents the signal distributions for CH-1 and CH-2 when beam of particles are impinging on the radiator. Since, there are very few signals corresponding to large PEs, the PE range is constrained to 60 PE. There are slightly more events with very large PEs for CH-2 than CH-1 but, below 10 PE, CH-1 generates many signals of amplitude 4 PE or larger.

There are 6053 events under consideration. It is calculated that number of event with light yield $> 5$ PE are 717 for CH-2, which is $\sim 12 \%$. In case of CH-1 MPPC, there are 1942 such events, which is $\sim 32\%$. Meanwhile, the average background is 0.42 PE for CH-2 and 1.03 for CH-1.

![Figure 6.19: Track distributions in the slice of width 5 mm intercepted by the rings of radii 25 and 30 mm: (left) rings centered around CH-1; (right) rings centered around CH-2](image)

6.5.1 **Comparison of Light Yield from CH-1 and CH-2 at Same Distance**

The distribution of tracks in the slice of glass of width 5 mm intercepted by the circle of radii 25 mm ad 30 mm centered on the MPPCs at CH-1 and CH-2 are shown in Fig. 6.19. Approximately, there are same number of tracks present in the both regions. The histograms are filled with calibrated signals for those two regions. Fig. 6.20 compares the distribution of PEs measured at CH-1 and CH-2 for those two regions. The number of events is almost
equal, however, average number of PEs detected by the MPPC at CH-1 is $3.9 \pm 0.2$ PE and the MPPC at CH-2 is $1.1 \pm 0.2$ PE. Thus, CH-1 has light output of 3.5 times that of CH-2.

### 6.6 Conclusion

From the above results it can be concluded that average number of photoelectrons generated in the MPPCs by the photons depends on the distance and distribution of the particle tracks from the center of the MPPC. However, the correlation of average light yield with the distance may be convoluted with other properties of glass like dispersive property. The dark noise of MPPC with larger photo sensitive area is higher than that for smaller one which could make it hard to resolve 1 PE signal. The Cerenkov light yield is small: number of events of $PE > 5$ PE $\sim 12\%$ for $3.5 \text{ mm} \times 3.5 \text{ mm}$ MPPC and that for $6 \text{ mm} \times 6 \text{ mm}$ MPPC is $\sim 32\%$. 
CHAPTER 7

SUMMARY

The REDTOP experiment depends upon the REDTOP detector for the study of the rare $\eta$ meson decays. The detector consists of three vital calorimeters: Fiber Tracker, Optical TPC and ADRIANO. ADRIANO dual-readout calorimeter is one of them which needs great advancement in technology. It consists of two instrumented active regions: the optical quality heavy lead-glass that has been chosen to work as an effective absorber as well as Cerenkov signal generator and plastic tiles as scintillating signal generators. ADRIANO2 prototype is designed to study the performance of those active media as a dual-signal generators.

Plastic tiles of size 10 cm $\times$ 10 cm $\times$ 0.4 cm are prepared with small dimples that fit 1.3 mm $\times$ 1.3 mm MPPCs. Glass blocks are sliced into tiles of size 10 cm $\times$ 10 cm $\times$ 0.98 cm. Automation codes for the CNC machine are finalized to make dimples on the glass. Moreover, the methods of polishing glass surface and the dimples are developed. BaSO$_4$ paint as reflector is extensively investigated in water-based as well as oil-based binders. The recipe for making paints and spraying corresponding to the four kinds of paints is developed. Also, their total reflectivity measurement is done using spectrometer. Paints made on water-based binders is measured to have reflectivity (total reflectivity $\sim$98%) comparable to that of ESR-2000 (total reflectivity $\sim$103%) in the spectral range of 390 nm - 750 nm. It is worth noting that barium sulfate paint in GAC-200 has better reflectivity than ESR-2000 in the low wavelength range. The test beam study of individual glass tiles with ESR wrapping and coating with barium sulfate paint is done with or without optical grease in the dimples.

Using ROOT/C++ scripts, the analysis of the signal generated inside the tile (as recorded by Hamamatsu MPPCs of sizes 6 mm $\times$ 6 mm and 3.5 mm $\times$ 3.5 mm)) is done for the run
This run corresponds to a glass tile wrapped in ESR-2000, dimples filled with optical grease and subjected to protons of energy 120 GeV, $\sim 50,000$ protons/spill in the beam line of Fermilab test beam facility. The results of analysis has given confidence that the ADRIANO2 prototype be studied at test beam for integrated response as well as for the study of other features of ADRIANO2.
BIBLIOGRAPHY


APPENDIX A

G-CODES FOR 8 MM MILLER
Spindle speed 7–8.

************

N1  G0  z0.80
N2  G0  X0.0000  Y0.0000
N3  M3
N4  G0  X1.0000  Y1.0000
N5  G0  Z 0.0010
N6  G1  z  -0.0094  F0.0020
N7  G0  z  0.1000
N8  G0  z  -0.0084
N9  G1  z  -0.0188  F0.0022
N10 G0  z  0.1000
N11 G0  z  -0.0178
N12 G1  z  -0.0281  F0.0021
N13 G0  z  0.1000
N14 G0  z  -0.0271
N15 G1  z  -0.0375  F0.0021
N16 G0  z  0.1000
N17 G0  z  -0.0365
N18 G1  z  -0.0469  F0.0021
N19 G0  z  0.1000
N20 G0  z  -0.0459
N21 G1  z  -0.0562  F0.0020
N22 G0  z  0.1000
N23 G0  z  -0.0552
N24  G1  z  −0.0656  F0.0020
N25  G0  z  0.1000
N26  G0  z  −0.0646
N27  G1  z  −0.0750  F0.0019
N28  G0  z  0.1000
N29  G0  z  −0.0740
N30  G1  z  −0.0844  F0.0019
N31  G0  z  0.1000
N32  G0  z  −0.0834
N33  G1  z  −0.0937  F0.0019
N34  G0  z  0.1000
N35  G0  z  −0.0927
N36  G1  z  −0.1030  F0.0019
N37  G0  z  0.1000
N38  G0  z  −0.1020
N39  G1  z  −0.1080  F0.0018
N40  G0  z  0.1000
N41  G0  z  −0.1115
N45  G1  z  −0.1175  F0.0018
N46  G0  z  −0.1000
N47  G0  z  −0.1170
N48  G1  z  −0.1219  F0.0018
N49  G0  z  0.1000
N50  G0  z  −0.1210
N51  G1  z  −0.1270  F0.0017
N52   G1   z  -0.1312  F0.0017
N53   G0   z  0.1000
N54   G0   z  -0.1302
N55   G1   z  -0.1350  F0.0017
N56   G0   z  -0.1200
N57   G0   z  -0.1342
N58   G1   z  -0.1406  F0.0017
N59   G0   z  0.1000
N60   G0   z  -0.1397
N61   G1   z  -0.1460  F0.0016
N62   G1   z  -0.1510  F0.0016
N63   G0   z  -0.1300
N64   G0   z  -0.1504
N65   G1   z  -0.1570  F0.0015
N66   G1   z  -0.1600  F0.0015
N67   G0   z  0.80
N68   G0   X1.0000  Y3.0000
   copy code N5–N67
N**   G0   X3.0000  Y3.0000
   copy code N5–N67
N**   G0   X3.0000  Y1.0000
   copy code N5–N67
N**   G0   X0.0000  Y0.0000
   copy code N5–N67
N**   M30

***************************************************************************
APPENDIX B

G-CODES FOR 10 MM MILLER
G-codes for 10 mm miller used to widen dimples made with 8 mm miller on glass. Spindle speed level: 4–5 until 
\[ z = -0.1300 \], then spindle speed level 6–7.

************************************************************

N1    G0 z0.5000
N2    G0 x0.0000 y0.0000
N3    M3
N4    G1 x1.0000 y1.0000 F30.00
N5    G0 z0.0010
N6    G1 z -0.0137 F5.000
N7    G0 z 0.1000
N8    G0 z -0.0122
N9    G1 z -0.0274 F5.000
N10   G0 z 0.1000
N11   G0 z -0.0259
N12   G1 z -0.0411 F1.000
N13   G0 z 0.1000
N14   G0 z -0.0396
N15   G1 z -0.0549 F1.000
N16   G0 z 0.1000
N17   G0 z -0.0534
N18   G1 z -0.0686 F0.500
N19   G0 z 0.1000
N20   G0 z -0.0671
N21   G1 z -0.0823 F0.500
N22  G0  z 0.1000  
N23  G0  z −0.0808  
N24  G1  z −0.0960    F0.0100  
N25  G0  z 0.1000  
N26  G0  z −0.0945  
N27  G1  z −0.1097    F0.0060  
N28  G0  z 0.1000  
N29  G0  z −0.1086  
N30  G1  z −0.1234    F0.0050  
N31  G0  z 0.1000  
N32  G0  z −0.1226  
N33  G1  z −0.1371    F0.0010  
N34  G0  z 0.1000  
N35  G0  z −0.1362  
N36  G1  z −0.1509    F0.0002  
N37  G0  z 0.1000  
N38  G0  z −0.1498  
N39  G1  z −0.1600    F0.0002  
N40  G0  z 0.1000  
N41  G0  z −0.1585  
N42  G0  z0.8000  

N43  G1  x1.000  y3.000    F30.00  

copy N5–N42  //those codes are same for all
N** G1 x3.000 y3.000 F30.00
 copy N5–N42

N** G1 x3.000 y1.000 F30.00
 copy N5–N42

N** G1 x0.000 y0.000 F30.00

N1** M30 //stops the program

***************************************************************