INFORMATION TO USERS

This reproduction was made from a copy of a document sent to us for microfilming. While the most advanced technology has been used to photograph and reproduce this document, the quality of the reproduction is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help clarify markings or notations which may appear on this reproduction.

1. The sign or “target” for pages apparently lacking from the document photographed is “Missing Page(s)”. If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure complete continuity.

2. When an image on the film is obliterated with a round black mark, it is an indication of either blurred copy because of movement during exposure, duplicate copy, or copyrighted materials that should not have been filmed. For blurred pages, a good image of the page can be found in the adjacent frame. If copyrighted materials were deleted, a target note will appear listing the pages in the adjacent frame.

3. When a map, drawing or chart, etc., is part of the material being photographed, a definite method of “sectioning” the material has been followed. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.

4. For illustrations that cannot be satisfactorily reproduced by xerographic means, photographic prints can be purchased at additional cost and inserted into your xerographic copy. These prints are available upon request from the Dissertations Customer Services Department.

5. Some pages in any document may have indistinct print. In all cases the best available copy has been filmed.
Calibration of a multi modular lead glass electromagnetic calorimeter

Krishna, Nety Murali, M.A.

Rice University, 1988
RICE UNIVERSITY

CALIBRATION OF A
MULTI MODULAR LEAD GLASS
ELECTROMAGNETIC CALORIMETER

by

NETY MURALI KRISHNA

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

MASTER OF ARTS

APPROVED, THESIS COMMITTEE:

Billy E. Bonner, Chairman
Chairman, Department of Physics
Director, T.W. Bonner Nuclear Laboratory
and
Professor of Physics

Abbas B. Roberts
Professor of Physics

Gordon S. Mutchler
Professor of Physics

Houston, Texas

April, 1988
ABSTRACT

CALIBRATION OF A
MULTI MODULAR LEAD GLASS
ELECTROMAGNETIC CALORIMETER

Nety Murali Krishna

We have studied the response of a lead glass electromagnetic shower detector by using an electron beam of 1 and 2 GeV. We present the results obtained from a study on position resolution of the detector. The stability of the calibration was monitored by using an LED system and an Am-source system. The position resolution varies for clusters with the number of blocks in the cluster. The average resolution is 2 cm. The detector was used in a "mock" experiment to reconstruct the $\pi^0$ mass by measuring the two photons coming from $\pi^0$ decay. We measure a mass of $135.5 \pm 12.5$ MeV for the $\pi^0$. The actual mass of the $\pi^0$ from the particle data booklet is 134.96. The width of the $\pi^0$ mass, which is a test of the energy resolution of the detector, gives $18%/\sqrt{E}$.
ACKNOWLEDGEMENTS

I take this opportunity to sincerely thank my advisor, Prof. B. E. Bonner, for his encouragement and help; Prof. J. B. Roberts for his supervision of the experiment and insights into physical principles.

Thanks to all the people who worked tirelessly to complete the calibration in the short time allocated to us. Special thanks to Francesca Nessi-Tedaldi and Marzio Nessi for their consideration, advice and guidance. I would like to thank Shaheen Tonse for his help and interest and Chris Moore for his immense help in getting around "bugs".

I acknowledge my debt to the members of the E771 collaboration who participated in the winter '86 run for a gentle enunciation into the techniques of high energy physics experiments.
# TABLE OF CONTENTS

Abstract ......................................................... i
Acknowledgements ............................................... ii
List Of Figures .................................................. v

1. INTRODUCTION ............................................... 1
   1.1 Electromagnetic Calorimetry ............................. 2
   1.2 Motivation ............................................... 5

2. LEAD GLASS DETECTOR ....................................... 9
   2.1 Shower Characteristics ................................. 9
   2.2 Description Of The Detector ......................... 14
   2.3 Assembly ............................................... 14
   2.4 Electronics Setup .................................... 22

3. SETUP AND EXPERIMENTS .................................... 26
   3.1 High Voltage Balancing ............................... 27
   3.2 The LED Trigger,LED ................................. 28
   3.3 The PED Trigger,PED ................................. 29
   3.4 Position Resolution Using Electrons,EMAP ........... 30
   3.5 The \( \Pi^0 \) Trigger,PIO ............................ 31

4. ANALYSIS & RESULTS ....................................... 35
   4.1 Gaussfitting .......................................... 36
4.2 PED, LED ........................................... 39
4.3 ABCALC ........................................... 49
4.4 EMAP ........................................... 52
4.5 PIO ........................................... 67

5. CONCLUSIONS ...................................... 72

References ........................................... 76
LIST OF FIGURES AND TABLES

Fig. 1  Spin asymmetry in inclusive $A$ production. 7
Fig. 2  Energy loss of electrons and photons in SF5 lead glass. 10
Table 1  Lead Glass Characteristics. 15
Fig. 3  Lead Glass Array. 16
Fig. 4  Spectral response of RCA 4900 phototube. 18
Fig. 5  Frequency distribution of LED light. 20
Fig. 6  Schematic view of the LED system and a lead glass module. 21
Fig. 7  Electron trigger. 23
Fig. 8  Lead Glass Trigger. 24
Fig. 9  Beamline and experimental setup. 33
Fig. 10  $\Pi^0$ trigger. 34
Fig. 11  ADC spectrum of block 101 for 1GeV incident electrons. 37
Fig. 12  ADC spectrum of block 4 for 1GeV incident electrons. 38
Fig. 13  Pedestal values for the blocks during the run. 40
Fig. 14  Comparison of pedestal fluctuations for blocks 8 and 41. 41
Fig. 15  Mean pedestal values for the detector array. 43
Fig. 16  LED values for the blocks during the run. 45
Table 2  Summary of "bad" LED blocks. 46
Fig. 17 Comparison of pedestal fluctuations for blocks 39 and 97. 47
Fig. 18 Frequency distribution of LED values. 48
Fig. 19 % variation of LED data set 3 vs data set 2. 50
Fig. 20 Mean LED values. 51
Fig. 21 Energy conversion factors for all the blocks. 53
Fig. 22 Total cluster energy in a 1GeV electron initiated shower. 54
Fig. 23 Difference between calculated and extrapolated electron position. 56
Fig. 24 Energy deposited in central block of the cluster. 57
Fig. 25 Difference between calculated and extrapolated electron position using two different methods to find the cluster center. 58
Table 3 Comparison of position resolutions. 61
Fig. 26 Electron track distribution for clusters with 1 block. 63
Fig. 27 Electron track distribution for sub-block X(2,3). 64
Fig. 28 Corrected positions of electron clusters. 65
Fig. 29 Double peak structure in cluster reconstruction. 68
Fig. 30a $\pi^0$ mass spectrum with MPS magnet on. 69
Fig. 30b $\pi^0$ mass spectrum without MPS magnet. 70
Fig. 31 LED values during the experiment. 73
Fig. 32 $\Sigma^0$ mass spectrum from the experiment. 74
CHAPTER 1

INTRODUCTION

The detectors employed in high energy physics experiments are designed to perform various functions such as to record the position of the particle or possibly the arrival time or even to identify the particle. The particle trajectory can be determined from the position coordinates. Precise timing helps in unscrambling the various products from the same interaction, which is useful when the interaction rate is very high. The identity of the particle is necessary to isolate the process of interest, which may be established by measuring its mass (simultaneous measurement of velocity and momentum), looking for its particular decay modes and from its observed interaction with matter via strong, electromagnetic, or weak forces.

Needless to say, no single detector is versatile enough to combine all the above functions into one measurement. All detectors are based on the principle that an interaction of the particle with the detector medium produces an observable signal. Most detectors make use of the electromagnetic interactions of the particle with the detector medium. Different detectors are built based on the nature of the interaction being exploited viz;

a. proportional counters, multiwire proportional chambers and drift chambers which detect the ionization of a gas when a particle passes through it.
b. scintillation counters which record the luminescence emitted by ionizing particles in certain media.

c. Cherenkov counters which measure the properties of the Cherenkov radiation. This is the radiation emitted when high energy charged particles pass through and excite the atoms of a dielectric medium. Part of this absorbed energy is reemitted as a coherent wavefront at a fixed angle (Cherenkov radiation) to the particle's trajectory.

d. calorimeters which detect the showers produced by high energy particles, and
e. other detectors like emulsions, transition radiation detectors, silicon strip detectors and flashtube hodoscopes which use other properties.

1.1 Electromagnetic Calorimetry

In the present work, we are interested in a particular type of detector namely the electromagnetic calorimeter. A calorimeter is a block of dense matter which intercepts the primary particle and causes it to deposit all or part of its energy inside the detector volume in a cascade of increasingly lower energy particles. This is called a shower. Eventually, most of the incident energy is dissipated and appears in the form of heat. A small fraction of the deposited energy is detectable in the form of a more practical signal e.g. scintillation light, Cherenkov light or ionization charge.
Calorimeters have many attractive features that allow them to supplement or replace information obtainable by large magnetic spectrometers [1]. Some of the chief advantages are listed below.

1. They are sensitive to both charged and neutral particles.

2. The shower development is a statistical process. The average number of secondary particles, $N$, is proportional to the energy of the incident particle. The uncertainty in energy resolution is governed by the statistical fluctuations of $N$ and hence the relative energy resolution, $\frac{\sigma}{E}$, improves as $\frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E}}$.

3. The length of the detector required to measure the particle energy, $E$, scales as $\ln E$, whereas for magnetic spectrometers the size scales as $\sqrt{E}$.

4. With segmented detectors, it is possible to get precise measurements of the position and angle of the incident particle.

5. Differences in response to hadrons, electrons and muons can be used for particle identification.

6. They can cover large solid angles with relative ease.

7. Their fast response time is good for operation at high event rates and the pattern of energy deposition can be used for event selection.

The main drawbacks are the large mass of the detector, the large number of associated readout channels and the cost.
The shower phenomenon is used in electromagnetic shower detectors to detect high energy electrons and photons. Detectors may consist of either a homogeneous absorber or a sandwich structure that samples the energy loss. Homogeneous detectors include NaI and Bismuth Germanate (BGO) crystal scintillators, scintillating glass, lead glass blocks, thallium-doped heavy liquid counters and liquid argon. The most common types of electromagnetic sampling calorimeters include metal-scintillator sandwich, metal-liquid argon ionization chamber and metal-gaseous proportional wire chambers.

This thesis reports the methodology used to calibrate a lead glass electromagnetic shower detector. Lead glass consists of \( \approx 50\% \) Pb by weight in glass. Addition of lead greatly reduces the longitudinal length required for total energy absorption, because of the high \( Z \) the particle loses energy more rapidly \[ \frac{dE}{dx} \propto Z^2, \quad X_{\text{rad}} = \frac{180A}{Z^2}, \] without affecting the detectable signal transmission.

Calibration is a study of the response of a detector to a beam with well defined characteristics viz; energy, trajectory and type. The properties of the detector so obtained can then be used in experiments to determine the characteristics of particles incident on the detector. A backup system is designed to monitor the detector and adjust for changes in the calibration parameters. These changes may be due to external conditions such as temperature, changes in monitoring system, photomultiplier gains or possibly to internal changes connected with radiation damage in lead glass (very long term change for low rate environments).
1.2 Motivation

This calibration was undertaken to study the energy and position resolution of the Notre Dame-BNL-MPS lead glass wall. The objective of this calibration was to use the lead glass wall in a subsequent experiment to detect the photons coming from $\Xi^0$ decay (E817'). The experiment is a continuation of the study of polarization transfer from a polarized proton beam to inclusively produced hyperons, specifically, $A^0$ and $\Sigma^0$ [2].

Large polarization effects were first observed by Bunce et al. [3] at high energies (300Gev) in 1976. These results were contrary to the prevalent ideas that due to the abundance of final spin states, the necessary coherent interference between the various amplitudes to produce sizeable polarization effects would diminish at high energies. Further experiments [4] showed that for inclusively produced lambdas in $pp$ and $p$-nucleus scattering the polarization has the following characteristics: 1) it is independent of beam energy; 2) it increases monotonically with $X_F$ and $P_T$ saturating at $P_T\sim 1$ Gev; 3) it is weakly dependent on the target type, varying inversely as the atomic weight; and 4) transverse to the production plane preferentially along $-p_A^x p_T$.

A semi-classical theory based on the parton recombination model was put forward by De Grand and Miettinen [5] to explain the polarization effects. In this model the hyperons are polarized due to the Thomas precession of the quarks in the recombination process. A
simple rule enunciates the principle which gives the polarization
signs:

"Slow partons preferentially recombine with their spins down in the
scattering plane while fast partons combine with their spins up."

The signs of the polarization are predicted correctly for all the hy-
perons studied so far but there are a few discrepancies in the pre-
dicted magnitudes. The model predicts $P_{L-} = \frac{1}{2} P_{L+}$ and $P_{\Sigma^-} = -P_{\Sigma^+}$
whereas data indicates that $P_{L-} \simeq P_{L^+}$ and $P_{\Sigma^-} \simeq -2P_{\Sigma^+}$ [6]. The first
part of the experiment (E817) studied the polarization effects on
inclusively produced lambdas from a polarized proton beam incident
on a Beryllium target [2]. Results show that the asymmetry, $A_N$, and the
polarization transfer, $D_{NN}$, to be close to zero in accord with the
prediction of the model for directly produced lambdas. However, 30%
of the observed lambdas come from $\Sigma^0$ production and decay. Taking
this fact into account the model predicts $A_N = 0.033$ and $D_{NN} = -0.055$.
Looking at Fig.1 we see that the data does not agree with the model so
well. It was clearly desirable to perform a measurement of $A_N$ and $D_{NN}$
parameters for $\Sigma^0$ directly. The $\Sigma^0$ decays via $\Sigma^0 \rightarrow \Lambda \gamma$ (B.R $\sim 100\%$).
The $\Lambda$ would be no problem as the original setup [1] would suffice. To
detect the photon however we would need a lead glass array (to cover a
large solid angle). As it takes a long time and a lot of money to
build such a detector, it was decided to use one which could be
borrowed readily from some other group. Thus it came about that this
particular calibration was undertaken in the summer of 1987.

The remainder of the thesis is organized as follows. Chapter 2
contains a description of the detector and the mechanism of shower
Fig. 1 Asymmetry in inclusive $\Lambda$ production from a polarized proton beam as function of $X_F$. 

Key:
- $0.5 \leq P_T < 0.8$
- $0.8 \leq P_T < 1.2$
- $1.2 \leq P_T < 2.0$ 

18.5 GeV

13.3 GeV (Key given above)
generation. The hardware used in the calibration is also described here. Chapter 3 describes the different experiments that were done during this period of three weeks. Chapter 4 shows the analysis of the data and describes in detail the techniques employed. Results are also presented here. We present the conclusions in chapter 5 and give results from E817 on the $\Sigma^0$ reconstructed mass and the stability of the LEDs.
CHAPTER 2

LEAD GLASS DETECTOR

2.1 Shower Characteristics

The processes of energy loss mechanisms for electrons, positrons and photons combine to generate a shower. Electrons and positrons lose energy while traversing a medium by ionizing the medium i.e; creation of positive ions by liberating electrons, undergoing radiative collisions where the particles are decelerated by the field of a nucleus and multiple scattering at low energies. Ionization energy loss is approximately constant and proportional to $Z$ whereas radiation loss is proportional to the energy of the particle and to $Z^2$. Thus at high energies, radiation losses dominate. Photons on the other hand can lose energy in three different ways: 1) photo-electric effect, 2) compton scattering, and 3) pair production. For energies greater than 100 MeV, photons lose energy almost entirely by pair production. Figure 2 shows the importance of the different energy loss mechanisms as a function of energy for electrons and photons in SF5 lead glass.

A high energy particle, say an electron, on passing through matter suffers a radiative collision. The energy change in the electron appears in the form of a photon (Bremsstrahlung). The characteristic length for this process is the radiation length, $X_0$. 
Fig. 2 Energy loss of electrons and photons vs incident energy. \text{COLLision, BREMsstrahlung, COMPton scattering, PAIR prod losses and $\delta$: total energy loss of photons.}
It is defined as the depth at which the average energy of the electron beam falls by a factor of e i.e;

\[ E = E_0 \exp \left( \frac{-x}{\lambda_0} \right) \]  \hspace{1cm} (2.1)

where \( E_0 \) is the initial energy. The photon converts into an electron-positron pair after travelling a distance called the conversion length, defined by:

\[ I = I_0 \exp \left( \frac{-7x}{9\lambda_0} \right) \]  \hspace{1cm} (2.2)

Thus for every radiation length of matter each electron loses on an average 63\% of its energy by photon production and each photon 54\% by pair production. These particles undergo similar transformations in the next radiation length and so on. This produces a shower of low energy particles. The energy degradation proceeds by the above mechanism until a critical point below which ionization losses compete with Bremsstrahlung and other dissipative forces become important.

Due to multiple scattering of the electrons, the shower also spreads transversely. The length scale for this process is the Moliere radius, \( \rho_m \), given by

\[ \rho_m = \frac{7A}{2} \]  \hspace{1cm} (2.3a)

or alternately by

\[ \rho_m = \frac{X_0}{21E_0} \]  \hspace{1cm} (2.3b)

where \( E_c \) is the critical energy of the medium. Roughly, 95\% of the shower is contained laterally in a cylinder of radius \( 2\rho_m \) for initial energies up to 10 GeV.

Cherenkov radiation from the shower products provides the detectable signal. The number of photons emitted by the Cherenkov effect, per unit interval of frequency is given by
\[ n(\nu) = \frac{2\pi a^2}{c} \left[ 1 - \frac{1}{n(\nu)^2 \beta^2} \right] \quad \ldots \ldots \quad (2.4) \]

where \( a = e^2/\hbar c \), is the fine structure constant. The energy loss due to Cherenkov radiation, neglecting the frequency dependence of \( n \), is given by

\[ \frac{dE}{dx} = \frac{4\pi^2 z^2 e^2}{c^2} \left[ 1 - \frac{1}{n^2 \beta^2} \right] \frac{\nu^2}{2} \quad \ldots \ldots \quad (2.5) \]

For SF5 lead glass a 1 Gev electron emits \( \sim 22 \) photons/unit frequency interval and the total energy emitted as Cherenkov radiation in the spectral limits 300nm to 600nm is \( \sim 12 \) Mev/m.

A mathematical description of the development of a general electromagnetic shower is extremely complex and cannot be solved in a closed form. By making several simplifying assumptions it is possible to calculate the expected shower development process. Some of these assumptions are listed here:

1. Consider only the average behaviour of the shower and fluctuations from the average.

2. The shower develops primarily in the forward direction. Treat the longitudinal and lateral developments independently.

3. Probabilities for pair production and Bremsstrahlung are assumed to be independent of \( Z \) when distances are measured in radiation lengths.

4. Deviations in cross-sections for electrons and positrons are neglected.

5. The asymptotic formulae for radiation and pair production are assumed valid.
6. Compton effect and collisional processes are neglected at high energy.

7. The shower stops abruptly when the energy of the particles falls below the critical energy, \( E_c \). The rest of the energy loss is assumed to be due to collisions.

Simple models bring out general features of the showers which show that the maximum number of shower particles is proportional to the energy of the incident particle. Quantitatively, accurate treatments of shower development are performed using Monte Carlo techniques. These calculations take into account the energy dependence of the cross section, the lateral spread of the shower due to multiple scattering, and statistical fluctuations. Given below are the results obtained by simulation of a photon initiated shower in SF5 lead glass [5].

1. The maximum energy loss occurs at

\[
\tau_{\text{max}} = 1.16 \left[ \ln \frac{E}{E_c} - 0.62 \right] \quad \ldots \quad (2.6)
\]

where \( E_c = 13.4 \text{MeV}/x_0 \).

2. The energy loss curve is given by

\[
y = A \cdot \tau^a \cdot e^{-bt} \quad \ldots \quad (2.7)
\]

where \( A = 8.58 \), \( a = 2.03 \), \( b = 0.468 \) for a photon with incident energy of 1GeV.

3. The total track length, which is the total path length traversed by electrons and positrons in the detector medium, is given by

\[
<T(E)> = E/E_c \quad \ldots \quad (2.8)
\]
2.2 Description Of The Detector

The detector consists of 129 blocks arranged in 10 rows to form a wall. Two different types of lead glass were used in the construction. They differed both in composition and size. Table 1 gives the salient features of both types of lead glass. The three upper and two lower rows consist of the larger, SF5 type, blocks. The smaller, SF2 type, blocks form the central layers. Figure 3 shows the arrangement of all the blocks. Alternate rows are staggered by half a block length to improve position resolution.

The detector also consists of ten scintillator strips arranged horizontally in front of the wall. Each strip covers one layer of lead glass blocks. The scintillator which detects ionizing particles is used to veto events where the shower is not initiated by photons. This is an important trigger requirement.

2.3 Assembly

The detector has to be arranged in such a manner that no extraneous light leaks into the lead glass blocks or the scintillator strips thereby generating spurious signals. The lead glass blocks are wrapped in blackened aluminized mylar on all the side faces. The end face is optically coupled to a lead glass cylinder called a cookie. This is done using a special grease which has the same refractive index as that of the lead glass being used. This reduces loss of signal by refraction. The cookie acts as a light guide by adapting the square face of the lead glass block to the circular face of the photomultiplier tube. At the other end of the cookie is the
### TABLE 1

**Lead Glass Characteristics**

<table>
<thead>
<tr>
<th></th>
<th>SF5</th>
<th>SF2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (gm/cc)</td>
<td>4.08</td>
<td>3.86</td>
</tr>
<tr>
<td>Refractive index, n</td>
<td>1.673</td>
<td>1.648</td>
</tr>
<tr>
<td>Radiation length, X₀ (cm)</td>
<td>2.36</td>
<td>2.62</td>
</tr>
<tr>
<td>Critical energy, E₀ (MeV)</td>
<td>15.8</td>
<td>17.5</td>
</tr>
<tr>
<td>Nuclear collision length (cm)</td>
<td>21.4</td>
<td>21.8</td>
</tr>
<tr>
<td>Atomic number, Z</td>
<td>34.81</td>
<td>31.79</td>
</tr>
<tr>
<td>Size (cm)</td>
<td>10.14</td>
<td>8.9</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>Length (X₀)</td>
<td>14.7</td>
<td>12.6</td>
</tr>
<tr>
<td>Molieres radius</td>
<td>3.14</td>
<td>3.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Comp</th>
<th>Mol. Wt.</th>
<th>%wt SF5</th>
<th>%wt SF2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>60.06</td>
<td>0.385</td>
<td>0.42</td>
</tr>
<tr>
<td>PbO</td>
<td>223.21</td>
<td>0.55</td>
<td>0.51</td>
</tr>
<tr>
<td>Na₂O</td>
<td>61.99</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>K₂O</td>
<td>94.19</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Fig. 3 A front view of the lead glass detector with the blocks numbered.
photomultiplier tube coupled in a similar fashion. An electronic base at the end of the phototube contains the voltage divider for the phototube. The electronics base has four spigots, two dynodes and one anode outputs and a high voltage input. One anode output goes to the trigger logic and the dynode output goes to the ADC modules. We used Le Croy 2249A model ADC modules. A brief description of these modules is given in appendix A.

For accurate determination of the particle energy, it is necessary to collect as much of the Cherenkov light on the front face of the photomultiplier tube as possible. The energy region for the operation of the lead glass ("a few GeV) and the area of the photo cathode prompted the use of the RCA 4900 teacup cage type phototubes. The phototube flares out at the cathode end to cover a circular area of 2.25π. This also determines the size of the cookie. The phototube has 10 amplification stages with a typical gain of 3×10^6. The photo cathode is made of KCsSb with a spectral response ranging between 300 and 660 nm. The peak spectral response occurs at 400 nm. Figure 4 shows the spectral response versus wavelength for the phototube.

Each LG block is illuminated at the rear by a pulsed light emitting diode, LED, system. This consists of a LED light source (HLMP 3950, green LED) which illuminates a bundle of 150 plastic fibre cables and associated electronics. The bundle is wrapped tightly with string and then enclosed in epoxy at one end. A filter wheel assembly of neutral density filters can be positioned to vary the light reaching the fibre optic bundle. Due to the bundle size and the position of individual fibers with respect to the light source, the LED fibers
Fig. 4 Spectral response of RCA 4900 phototubes.
are not illuminated uniformly. The illumination distribution is shown in fig. 5 for all the fibers with a standard tube. We see that the illumination varies from 125 to 680 ADC channels with 60 fibers lying between 300 and 400 ADC channels.

Each fibre optic cable consists of seven individual plastic strands. These strands are epoxied at each end and polished to increase light transmission. A plastic tubing covers each cable (seven strands) which is approximately 1000 microns in diameter. The LED fibre is then inserted through a three feet copper tubing so that one end rests against the face of the lead glass.

The lead glass modules are packed together in a grid box. The front face is covered with layers of sponge and boarded up with an aluminium plate to form a planar surface. The cookie is housed in a cylindrical shell at the other end of the box. The phototube is covered by a blackened cylindrical shell of aluminium which extends till the cookie joint. This insures against stray light leaking in from the back. The base is pinned into the tube. The phototube and base assembly is surrounded by a mu metal shield which protects it from magnetic fields which upset the focussing conditions in the phototube. (The field lines are bent and stay inside the shield.) The base and tube assembly is kept in a horizontal plane by a spring mechanism. This insures against the phototube face slipping thereby resulting in light losses. A schematic view of one of the modules is shown in Fig. 6.

The high voltage is supplied to all the blocks by LeCroy HV1440 power supply. This is a multiprogrammable system with high long term
Fig. 5 Frequency distribution of LED light in the fiber optic bundle for a standard tube.
Fig. 6  Schematic view of the LED system and the lead glass module.
stability (2V/week). The supply is controlled via a CAMAC interface for issuing commands and monitoring the voltage stability. This is convenient because the supply is situated inside the radiation security area, and local interaction is via a hand controller which is quite cumbersome.

The whole detector assembly - LG wall, LED system, the HV power supply and some electronics racks is placed on a RoL-lift hydraulic platform. The platform consists of crossed co-axial piston legs which allow vertical motion of the platform. It rests on four air-pads which allow horizontal motion. The platform can move 2m vertically and anywhere in the horizontal plane.

2.4 Electronics Setup

The triggering system was organized to handle various triggers remotely by throwing a switch. Relative timing was done against a set of scintillators, S, which are also the first trigger elements in the beam line. A set of hole scintillators was used to limit the beam spot, and Cherenkov counters to select electrons. This defines the beam (Fig.7). The lead glass electronics was arranged to give a sum of pulse heights from each row. The OR of all the rows was sent to the "fast trailer", which houses all the electronics racks etc. Signals from each of the ten veto scintillators were also sent to the FT (Fig.8) The set of signals from the dynodes on the lead glass blocks were sent to the ADC modules for pulse height digitization and subsequent readout by the computer via CAMAC interface.
FIG. 7 ELECTRON TRIGGER
Fig. 8 LEAD GLASS TRIGGER
The DT FI contains the OR of the various dead times in the data acquisition system. These consist of the times when the trigger was busy with an event or the computer was busy storing data on tape. The trigger dead time originates from the finite time it takes for each electronics module to process the input signal, e.g. discriminators, FIFOs (fan-in fan-outs) take ~10 ns to generate the output signal, ADCs take ~250 µs. Dead time also occurs due to data being transferred on CAMAC Dataways.
CHAPTER 3

SETUP AND EXPERIMENTS

The calibration was performed in the Multi Particle Spectrometer (MPS) at Brookhaven National Laboratory. The beam was transported in the secondary beam line, B2, which is a medium energy beamline.

The setup time, before the beam was on, was used in moving, cleaning and removing extraneous material from the detector like the a/c housing etc. The calibration proceeded in steps from adjusting the high voltage on the phototubes to obtain energy vs ADC linearity curves (High Voltage Balancing), to taking electron shower data for position reconstruction (EMAP), and ending by taking PI0 trigger to test the detector in an actual experimental environment. Data was also taken during all the above runs to monitor the various parts of the hardware (LED, PDE, REF) and to understand their influence on the energy and position reconstruction.

The first step was to mark off the block positions on the detector. An indexed paper on the side of the platform and a tape mark on the front face of the detector made it possible to tell where each block was behind the scintillators and the Al plate cover. The block sizes calculated from the above measurements give 10.26x10.26 cm² and 9.14x9.14 cm² for big SF5 and the smaller SF2 respectively. The bare block size is 10.16 cm² and 8.99 cm² respectively. The extra
millimeter or so is presumably the width of the wrapping on each block.

3.1 High Voltage Balancing

The ADC can count up to a maximum of 1024 channels. It is necessary to set the scale of the ADC for the energy regime of interest. This was done by adjusting the high voltage on each block separately to give a predetermined ADC value for a beam of fixed energy. The HV was adjusted for a full scale of approximately 3 GeV electron. This was done by shooting a beam of 2 GeV electrons through the center of each block. A 1 cm² scintillator (S10) placed at the centre of each block defined valid triggers. This was done to avoid leakage of the shower into neighbouring blocks thereby reducing the output pulse and the resolution. The trigger for this part is

\[ e^- . S10 \]

where \( e^- \) is the electron beam defined in section 2.4. The HV was adjusted for the ADC spectrum to peak at 700.

For balancing all the blocks the LG platform and S10 were moved into beam path. The beam spot was big enough for analysing 3-4 blocks before the detector had to be moved to its next position. Each measurement consisted of five readings:

a. a HV setting at \( \sim \) 800 ADC counts - HV(HIGH),
b. a HV setting at \( \sim \) 600 ADC counts - HV(LOW),
c. a HV setting at \( \sim \) 700 ADC counts - HV(OPT),
d. LED, and
e. PED
HV(OPT) was extrapolated on a straight line using HV(HIGH) and HV(LOW)

\[
HV(\text{opt}) = HV(\text{HIGH}) - \frac{\text{ADC(\text{HIGH})} - 700}{\frac{\text{ADC(\text{HIGH})} - \text{ADC(\text{LOW})}}{HV(\text{HIGH}) - HV(\text{LOW})}}
\]

The beam line then was retuned for 1GeV electrons. The measurements at this energy consisted of:

a. an ADC spectrum at HV(OPT),

b. LED, and

c. PED.

As the ADC counts scale linearly with energy, we expect the spectrum to peak at 350 counts for all blocks. Online analysis gave reasonable results.

3.2 LED

For taking LED data, the beam trigger was switched off and the LED trigger was turned on, which starts the LG pulser shown in (fig.7). This fakes the electron beam and the system is ready to acquire data. The pulser acts as a switch for the LED lamp which is set at 100 Hz i.e. the LED lamp goes through a cycle of on-off, 100 times/second. Only a few of these pulses are taken as data because of the dead time in the electronics and the limited size of the data buffers. It was efficient to write 32 triggers/spill. The spill is the time length when the beam pulse is on. An overall gate from the accelerator control center defines this period. A spill occurs every 2 secs and lasts for ~800 msecs.
The readings from the ADC value give the amount of light transmitted to that particular block from the LED source. LED sources are chosen which have a long lifetime and are stable from pulse to pulse. A typical LED can last for approximately $10^7$ pulses before any sign of fatigue i.e., diminished light output occurs.

Since the HV of the LG modules will not be altered after they have been adjusted and the light output is expected to remain constant, the LED is very useful as a monitoring source for changes in the phototubes. Unfortunately, the LED output gets affected by external temperature. To overcome this problem, a separate trigger was set up using an Am 241 α source as a stable light source. Am has a lifetime of 432.2 years and emits α's at 5486 KeV. The Am source was taped on a 1 cm square piece of scintillator which in turn rested on the face of a photomultiplier tube. The excitations in the scintillator from the Am alpha rays are collected by the phototube and the pulse is digitized by the ADC (REFerence trigger). Since the alpha-source has a long lifetime, this monitors fluctuations in light output from the LED. Another monitor for the LED output is the average of LED ADC values from all blocks for a single pulse.

3.3 PEDESTAL

The pedestal trigger is set up along parallel lines as the LED trigger. The main difference is that the pulser does not turn on the LED lamp. The pedestal is the ADC channel number that gets incremented when a gate pulse is applied with no analog input. The pedestal is largely due to charge injected into the ADC capacitor for
a null signal and a factory set dc level (~4mV). The dc offset is set to assure proper working of the unit in case the dc level of the input should drift. Due to the DC coupling the pedestal has a temperature dependence, too.

Residual Pedestal = 1 + 0.3t picocoulombs, t=gate duration.

The pedestal is unique for each individual ADC and has to be subtracted from each output signal. There is no reason for the pedestal to fluctuate and it is expected to be very stable.

3.4 EMAP

This part of the calibration was done to study the position resolution of the array. In the actual experiment the photons will not be restricted to the center of each block. An event would normally consist of more than one active block in the LG array and both the energy and the position of the incident particle are extracted by looking at the cluster. An active block is defined as having an ADC count of at least 30% more than its pedestal value. This is a qualitative cutoff and was chosen so that it is large enough to exclude noise or fluctuations in the ADC channel and small enough to include all blocks which contain a significant part of the shower.

In the actual experiment we will be looking at photon initiated showers. Since the photon's entry point cannot be tagged, its point of entry has to be estimated by indirect means. This can be done by finding the centroid of the distribution of energy in the cluster or some other method.
The electron mapping (EMAP) data consists of electron initiated showers. The electron is tracked with drift chambers and proportional wire chambers. As there is no magnetic field, the tracks are straight and can be extrapolated with good accuracy from the last chamber to the front face of the LG. This gives the entry point of the electron. Three sets of data were taken, with the beam centered on block (56,69), 96 and 119 respectively.

3.5 The \( \pi^0 \) Trigger

The \( \pi^0 \) is produced quite abundantly in high energy collisions. The \( \pi^0 \) trigger was set up to study the energy resolution of the detector. The layout of the experiment is shown in fig.9. The beam line was tuned for 3 GeV secondary particles. These consist of \( \pi^- \), \( K^- \) and pbars. They are produced by the primary proton beam interacting with a Pt wire in the beamline upstream of the experimental setup. The secondary particles then interact with the polyethylene target \( [(CH_2)_n] \) placed upstream of the MPS magnet. Pions are produced by pion-nucleon scattering,

\[
\pi^- p \rightarrow \pi^0 n \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.1)
\]

\[
\pi^- p \rightarrow \rho^- p
\]

\[
\rightarrow \pi^0 \pi^- (p) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.2)
\]

associated production of hyperons and their subsequent decay,

\[
\pi^0 p \rightarrow \kappa^0 \ \Lambda
\]

\[
\rightarrow (2\pi^0) \ (n\pi^0) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.3)
\]

\[
\pi^- p \rightarrow \kappa^0 \ \Sigma^0
\]

\[
(2\pi^0) \ (\Lambda \gamma) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.4)
\]
and from

\[ \kappa^- p \rightarrow \Lambda \eta \]

\[ (n \pi^0) (\pi^+ \pi^- \pi^0) \]  \hspace{1cm} (3.5)

\[ \kappa^- p \rightarrow \pi^0 \Sigma^- \]  \hspace{1cm} (3.6)

\[ \kappa^- p \rightarrow \pi^0 \Lambda^0 \]  \hspace{1cm} (3.7)

\[ \kappa^- p \rightarrow \pi^0 \pi^0 \Sigma^0 \]  \hspace{1cm} (3.8)

The charge exchange cross section, (3.1), dominates the \( \pi^0 \) production.

The associated production reaction (3.3) is less by a factor of 200 [8,9]. The trigger is set up to detect two simultaneous photon initiated showers which come from the \( \pi^0 \rightarrow \gamma \gamma \) decay. The MFS magnet was switched on to sweep all charged particles away from the lead glass. This reduces the background and improves the trigger rate. Fig.10 shows the essential part of the logic which comprised the \( \pi^0 \) trigger.
Fig. 9. Layout of the beamline and lead glass detector.
Fig. 10 $\pi^0$ TRIGGER
CHAPTER 4

ANALYSIS AND RESULTS

The primary analysis of the raw data was done at Brookhaven in June 1987. Data summary tapes (DSTs) were produced using the various computers available: BNLHEP (Vax8600), BNLDAQ (Vax 780), BNLMP (Vax 750) and BNLCL2 (a cluster of five Vax 780s). The data consisted of the following: 1) binary files containing spectra for all the blocks at 1 and 2 GeV which would give the mean positions of the ADC channels for both the energies (Gaussfitting data); 2) mean values of the LED, PED and REF runs; 3) electron tracks showing where they entered the lead glass detector along with all the active blocks; and 4) data from the photon initiated showers coming from $\Pi^0$ decay.

Analysis of the binary files along with corrections from the PED runs gives a relationship between the energy deposited in the lead glass and the channel number in the ADC output. This information is then used to calculate the energy deposited in any block by looking at the channel number. The EMAP data shows how the shower spreads laterally and the corrections that can be applied to deduce the entry point of the particle more accurately. The Pi0 trigger is designed to bring out unusual problems in reconstructing more than a single shower and it provides an environment to test the detector efficiency.
4.1 Gaussfitting

We obtain a distribution for the energy deposited in the block for a beam of fixed energy because the energy loss mechanisms are statistical in nature. An analytical gaussian was fitted to the distribution for each block at 1 and 2 Gev to obtain the mean of the spectrum. Each binary file contained 2.5K events on average. The mean, standard deviation and chi-square of each fit were stored in a separate file. The form of the gaussian chosen for the fit is given by

\[
A \times \exp \left( -\frac{1}{2} \left( \frac{X-B}{C} \right)^2 \right) \]

(4.1)

The best fit was determined by the height (A), the mean value (B) and the width (C) of the gaussian, the three free parameters. To remove personal bias in choosing the best fit, the fits were examined by two other people. Fig.11 shows the 1Gev spectrum for block\# 101. The blocks which are closest to the platform are generally very broad and not as well defined as the ones away from the platform. This is due to the showering from the beam hitting the platform which is made of steel. Fig.12 shows the ADC spectrum for block\# 4. Notice how much broader the distribution is than that for block\# 101 in Fig. 11. The spectrum falls off sharply beyond the peak but tends to be less steep before the peak. We see this behaviour in all blocks to some extent. The origin of this asymmetry is shower leakage into neighbouring blocks. Although the trigger requires the beam to go through a 1 cm² scintillator (S10), angular incidence can broaden the spectrum. Another possibility is for a shower product formed upstream of the
Fig. 11 ADC spectrum of BI#101 for a 1GeV electron.
Fig. 12 ADC spectrum of Bl#4 for a 1GeV electron.
lead glass to trigger S10. The gaussian is fitted to make each side of the mean fall off equally as it would in an ideal situation.

4.2 PED, LED

The pedestals (PED) were taken once every hour. The data was broken up into three sets. Data taken during a) 2GeV gaussfitting, b) 1GeV gaussfitting + EMAP, and c) π⁺. There is no particular reason to break the data up for the pedestals, but it is necessary for the LED data.

The deviation of each pedestal from a reference run (chosen arbitrarily) was plotted against the run number (i.e., time). Four to five reference runs were used. The number plotted was: PED (run number) - PED (reference run) + 6 versus run number. This was done to see at a glance if there were any problem spots or problem runs. Three runs which were not pedestal runs had been stored accidentally. These were removed and the means were calculated for all runs in each set. Figure 13 shows the PEDs for each data set with the block number on the x-axis and the mean ADC value on the y-axis. PED1 corresponds to the pedestals for data set 1 and so on. We can see that the shape of the three plots is the same. The error bars on each mean value reduce as time goes on. This shows that the system is stabilising. Figure 14 shows the fluctuations in a good and a "bad" block as a function of run number (i.e., time). The first 128 runs belong to the first, the next 55 runs to the second and the last 10 runs to the third data sets respectively. region. The problem observed in bl# 8 is not due to the ADC module because the same effect is observed if a different ADC
Fig. 13 PEDESTAL ADC values for all the blocks during the calibration period.
Fig. 14 A comparison of pedestal fluctuations for a) block# 8 and b) block# 41.
input is used. The dc level is fluctuating due to the tube or the base, consequently changing the pedestal value. To see the stability of the pedestals, we have plotted the difference for two data sets at a time. We observed that they were all zero within two channels.

In all there were four bad PED channels: 7, 59, 92, 119, for which the pedestal values were fluctuating a lot. The other "bad" blocks have a periodic fluctuation which is not so large. The mean pedestals for all the blocks is given in fig.15. The pedestals run between 11 and 43 ADC channels for all the blocks.

The LED data was also taken once every hour. This is used for monitoring the fluctuations in the phototube's output. The LED data was also broken up into three data sets. The first part is the 2 GeV gaussfitting region. During this period, the HV on each tube was being adjusted to get 700 ADC counts for a 2 GeV particle through the center of the block. The LED values are thus not stable yet. The second and the third data sets correspond to the 1 Gev and pi0 regions respectively. In the last week, an extra tube with an LED fibre and an Am 241 alpha-source was added. Being more stable than the LED, the Am source ADC values give a relative calibration for the LED. During data taking, approximate pedestals were stored in a file from a short pedestal run. These pedestals were subtracted from each LED value before being stored on tape. The preliminary analysis of each LED file produced a mean value of ~1000 LED pulses. This value was stored in a file. During offline analysis, each LED value was adjusted for the correct pedestal value shown in Fig.15. The mean PED values from each
<table>
<thead>
<tr>
<th>20.0.2</th>
<th>24.0.3</th>
<th>22.0.4</th>
<th>22.0.3</th>
<th>24.0.5</th>
<th>21.0.2</th>
<th>25.0.3</th>
<th>23.0.4</th>
<th>22.0.3</th>
<th>21.0.3</th>
<th>23.0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.0.1</td>
<td>33.0.2</td>
<td>25.0.1</td>
<td>19.0.3</td>
<td>22.0.3</td>
<td>21.0.2</td>
<td>23.0.2</td>
<td>24.0.2</td>
<td>23.0.3</td>
<td>22.0.2</td>
<td>27.0.2</td>
</tr>
<tr>
<td>37.0.3</td>
<td>32.0.3</td>
<td>38.0.4</td>
<td>18.0.5</td>
<td>19.0.4</td>
<td>13.0.2</td>
<td>28.0.2</td>
<td>35.0.2</td>
<td>21.0.2</td>
<td>31.0.3</td>
<td>25.0.2</td>
</tr>
<tr>
<td>19.0.3</td>
<td>21.0.3</td>
<td>24.0.5</td>
<td>22.0.4</td>
<td>17.0.3</td>
<td>21.0.3</td>
<td>26.0.4</td>
<td>23.0.4</td>
<td>21.0.4</td>
<td>16.0.3</td>
<td>24.0.3</td>
</tr>
<tr>
<td>21.0.4</td>
<td>17.0.4</td>
<td>18.0.5</td>
<td>17.0.5</td>
<td>19.0.4</td>
<td>23.0.4</td>
<td>19.0.5</td>
<td>29.0.4</td>
<td>11.0.3</td>
<td>39.0.5</td>
<td>38.0.4</td>
</tr>
<tr>
<td>41.0.2</td>
<td>34.0.2</td>
<td>40.0.2</td>
<td>41.0.4</td>
<td>40.0.3</td>
<td>32.0.4</td>
<td>21.0.5</td>
<td>21.0.1</td>
<td>18.0.7</td>
<td>15.0.4</td>
<td>21.0.3</td>
</tr>
<tr>
<td>27.0.1</td>
<td>21.0.3</td>
<td>15.0.2</td>
<td>14.0.2</td>
<td>25.0.2</td>
<td>27.0.2</td>
<td>23.0.3</td>
<td>27.0.2</td>
<td>27.0.2</td>
<td>26.0.3</td>
<td>28.0.2</td>
</tr>
<tr>
<td>24.0.2</td>
<td>28.0.2</td>
<td>18.0.2</td>
<td>29.0.3</td>
<td>39.0.4</td>
<td>21.0.3</td>
<td>31.0.4</td>
<td>36.0.4</td>
<td>27.0.4</td>
<td>26.0.2</td>
<td>28.0.2</td>
</tr>
<tr>
<td>29.0.3</td>
<td>29.0.2</td>
<td>36.0.3</td>
<td>38.0.3</td>
<td>29.0.3</td>
<td>33.0.4</td>
<td>38.0.3</td>
<td>30.0.3</td>
<td>26.0.4</td>
<td>14.0.6</td>
<td>38.0.5</td>
</tr>
<tr>
<td>27.0.4</td>
<td>30.0.2</td>
<td>39.0.2</td>
<td>34.0.5</td>
<td>27.0.7</td>
<td>28.0.4</td>
<td>36.0.7</td>
<td>24.0.4</td>
<td>26.0.4</td>
<td>11.0.3</td>
<td>27.0.3</td>
</tr>
</tbody>
</table>

Fig. 17 Mean PEDestal values with statistical errors for all the blocks. The block numbers are shown in Fig. 3.
data set were used to correct the mean LED value for that set. The corrected LED values are plotted for all three data sets in figure 16.

The LEDs fluctuate more than the PEDs because 1) the LED pulse is big so any timing fluctuations can result in part of the pulse lying outside gate which can result in a lower ADC value, 2) The LED output can vary due to temperature, 3) phototube fluctuations, and 4) disturbing the fiber can change the its orientation with respect to the lead glass surface resulting in a varied reading. The last effect was minimal because of the long tube (~3 feet) through which the fibre was inserted to touch the surface of the lead glass. We set a limit of +3 % to -3 % on the fluctuation of the LEDs for a good module. The scatter plot of the adc deviations from a reference run showed 14 modules to be bad. On examining the ADC values instead of deviations, most of them had bad patches which lasted a couple of hours. The reading otherwise was stable and this was used as the mean. The first few runs of data set 2 are bad. This is due to the long time it takes the phototubes to stabilize. There is a strong correlation between the order in which the 2 GeV gaussfits were done and the blocks which have the first few runs bad in 1 GeV gaussfitting region. Table 2 gives a summary of the bad LED blocks. The LED plot shown in figure 16 has been corrected for all the bad runs. Figure 17 shows a good and a bad LED value against the run number. Notice how the ADC value fluctuates for block 39. Figure 18 shows the LED values for all the blocks binned according to ADC values. The difference from the LED light distribution (fig 5) is due to the different HV used. We can see from the histograms that the phototube gains are still reasonable.
Fig. 16 LED ADC values with statistical errors for all the blocks. Sets 1, 2 and 3 refer to different periods of the run.
**TABLE 2**

Table of "bad" LED blocks.

<table>
<thead>
<tr>
<th>Block #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initially bad (from scatter plot)</td>
</tr>
<tr>
<td>2, 7, 9, 11, 12, 21, 30, 39, 59, 79, 88, 92, 105, 119</td>
</tr>
<tr>
<td>Have first few runs bad</td>
</tr>
<tr>
<td>11, 12, 30, 88, 92, 105</td>
</tr>
<tr>
<td>Fluctuate</td>
</tr>
<tr>
<td>9, 39, 79</td>
</tr>
<tr>
<td>ADC value increases due to mag field</td>
</tr>
<tr>
<td>39, 119</td>
</tr>
<tr>
<td>ADC value decreases due to mag field</td>
</tr>
<tr>
<td>2, 21</td>
</tr>
<tr>
<td>List of bad blocks</td>
</tr>
<tr>
<td>7, 9, 39, 59, 79</td>
</tr>
</tbody>
</table>
Fig. 17 A comparison of LED fluctuations for a) block # 39 and b) block # 97.
Fig. 18 Frequency distribution of LED values for all the blocks with individual tubes.
The dip in figure 18 comes because we have data for the LED from only 129 blocks whereas figure 5 shows the light distribution for 150 fibers. In figure 19 we see the difference in ADC values for sets 2 and 3. The mean difference is 5 ADC channels. The variations for most of the blocks are within 3%. The LED values range from 45 to 597 ADC channels. The final mean values for each block are given in figure 20. Data from the REF trigger was sparse and fluctuating more than an average LED. No corrections were applied to the LEDs using the REF trigger.

4.3 ABCALC

To convert an ADC value for any event to the energy of the particle, we need to know how the module behaves at that high voltage. We can get parameters for each block from the 1 and 2 GeV gaussfitting curves. Each mean value from the gaussfit was corrected for the pedestals subtracted during data taking. A least square fit was done to obtain the slope and intercept for each module. The curve is:

\[ \text{Energy} = A + B \times \text{GaussfitMean} \]  
(4.2)

The momentum of the beam was determined using the dipole bending magnet D in the beam line and drift chambers in the MPS. We obtained 2.070 ± 0.056 and 1.063 ± 0.034 for the 2 and 1 GeV beams respectively.

The gaussian from the fit has a width which is the error in the determination of the mean, \( \sigma \). A subjective error was also estimated by looking at the curve and determining within what range an acceptable peak of the gaussian could lie, \( \delta m \). The error on the mean
Fig. 19  % variation of LED data set 3 vs data set 2.
| 279±1.2 | 190±1.1 | 357±2.8 | 279±6.1 | 522±3.9 | 498±2.6 | 598±6.8 | 401±2.6 | 342±1.6 | 285±1.3 | 277±5.7 |
| 247±1.1 | 251±1.2 | 340±2.0 | 247±1.2 | 289±1.0 | 294±1.3 | 213±1.2 | 339±1.8 | 440±1.8 | 287±1.2 | 228±1.0 | 338±1.5 |
| 196±1.4 | 138±0.5 | 472±1.8 | 354±1.4 | 375±1.7 | 293±2.1 | 93±0.5 | 333±1.2 | 299±1.4 | 413±1.6 | 226±1.3 | 350±1.4 | 488±1.8 |
| 266±1.1 | 159±1.3 | 334±1.4 | 480±1.5 | 331±1.8 | 163±2.1 | 448±2.0 | 106±0.6 | 6358±1.6 | 236±1.4 | 4446±4.7 | 330±1.8 | 254±1.7 | 408±2.9 |
| 388±3.0 | 511±6.1 | 505±2.4 | 253±1.9 | 197±1.6 | 548±2.4 | 372±2.4 | 406±3.1 | 276±1.1 | 383±2.5 | 248±1.6 | 231±1.1 | 401±2.2 |
| 288±1.3 | 369±2.2 | 300±1.7 | 385±2.3 | 331±1.2 | 383±1.7 | 214±1.7 | 206±4.0 | 571±3.0 | 159±0.8 | 185±1.0 | 236±1.2 | 338±1.4 | 83±0.7 |
| 346±1.5 | 159±1.2 | 223±1.3 | 214±1.1 | 160±0.7 | 464±1.9 | 438±1.7 | 139±0.8 | 331±1.2 | 269±1.6 | 371±1.7 | 344±1.4 | 201±0.9 |
| 418±7.6 | 342±1.2 | 260±1.5 | 206±1.4 | 324±1.1 | 328±3.6 | 212±0.5 | 294±1.3 | 181±1.6 | 241±1.4 | 120±1.1 | 335±1.6 | 275±1.2 | 275±1.1 |
| 294±1.3 | 58±0.4 | 196±0.9 | 215±0.8 | 45±1.2 | 254±1.6 | 181±0.9 | 280±1.1 | 242±2.0 | 266±1.4 | 127±1.2 | 265±1.2 | 212±0.9 |
| 290±1.5 | 321±1.9 | 201±1.4 | 185±3.3 | 213±1.6 | 890±5.2 | 458±2.5 | 357±2.3 | 219±0.8 | 343±2.1 | 56±1.2 | 211±0.9 |

Fig. 22 Mean LED values with statistical errors for all the blocks. The block numbers are shown in Fig. 3.
(x-axis) was combined with the error in the beam energy (y-axis) and transferred to the y-axis viz.

$$\text{Total error} = \sqrt{(\delta E^2 + \sigma^2 + \delta m^2)} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ (4.3)$$

The slopes for each block are given in figure 21.

4.4 EMAP

The bulk of the calibration data consists of electron events. These are showers produced by a beam of 1 GeV electrons. The data was analysed in stages by putting various cuts to improve the position resolution. The basic idea was to estimate the position of the electron using the energy distribution in the lead glass and find correction parameters using the extrapolated position of the electron. As the object of this exercise is to correct the estimated center for the photon shower, it is useful to know how the electron track behaves as a function of the estimated position.

To begin with, the analysis ignored all blocks that lie on the edges. The initial step was to make energy cuts to accept showers generated by 1 GeV electrons and not by the products of some interaction upstream of the lead glass. The minimum energy in a valid cluster was chosen to be 0.8 GeV. Figure 22 shows the energy distribution for clusters in the lead glass and the cut.

Another initial parameter to be looked at was the position of the lead glass with respect to the beam. We measured the position during the run using a scale and a plumbline. A more accurate determination during analysis was obtained by histogramming the
| 2.98*10^{-3} | 2.98*10^{-3} | 2.91*10^{-3} | 3.01*10^{-3} | 2.86*10^{-3} | 2.95*10^{-3} | 2.98*10^{-3} | 2.95*10^{-3} | 3.03*10^{-3} | 2.95*10^{-3} | 2.98*10^{-3} | 2.98*10^{-3} |
| 2.95*10^{-3} | 2.92*10^{-3} | 2.99*10^{-3} | 3.02*10^{-3} | 2.93*10^{-3} | 2.97*10^{-3} | 2.92*10^{-3} | 2.99*10^{-3} | 2.90*10^{-3} | 2.98*10^{-3} | 2.98*10^{-3} | 2.92*10^{-3} |
| 2.91*10^{-3} | 3.04*10^{-3} | 2.97*10^{-3} | 2.93*10^{-3} | 3.02*10^{-3} | 2.92*10^{-3} | 2.99*10^{-3} | 2.93*10^{-3} | 2.86*10^{-3} | 2.95*10^{-3} | 3.01*10^{-3} | 2.95*10^{-3} |
| 2.96*10^{-3} | 2.95*10^{-3} | 2.99*10^{-3} | 0.82*10^{-3} | 0.72*10^{-3} | 0.74*10^{-3} | 0.73*10^{-3} | 0.67*10^{-3} | 0.72*10^{-3} | 0.62*10^{-3} | 0.72*10^{-3} | 0.72*10^{-3} |
| 2.95*10^{-3} | 2.97*10^{-3} | 0.73*10^{-3} | 0.83*10^{-3} | 0.73*10^{-3} | 0.98*10^{-3} | 0.82*10^{-3} | 0.72*10^{-3} | 0.72*10^{-3} | 0.72*10^{-3} | 0.72*10^{-3} | 0.72*10^{-3} |
| 2.94*10^{-3} | 2.97*10^{-3} | 3.10*10^{-3} | 0.72*10^{-3} | 0.10*10^{-3} | 0.82*10^{-3} | 0.73*10^{-3} | 0.82*10^{-3} | 0.10*10^{-3} | 0.83*10^{-3} | 0.73*10^{-3} | 0.83*10^{-3} |
| 2.95*10^{-3} | 2.97*10^{-3} | 0.73*10^{-3} | 0.83*10^{-3} | 0.21*10^{-3} | 0.73*10^{-3} | 0.82*10^{-3} | 0.73*10^{-3} | 0.10*10^{-3} | 0.83*10^{-3} | 0.73*10^{-3} | 0.83*10^{-3} |
| 2.95*10^{-3} | 2.97*10^{-3} | 0.73*10^{-3} | 0.83*10^{-3} | 0.21*10^{-3} | 0.73*10^{-3} | 0.82*10^{-3} | 0.73*10^{-3} | 0.10*10^{-3} | 0.83*10^{-3} | 0.73*10^{-3} | 0.83*10^{-3} |
| 2.95*10^{-3} | 2.97*10^{-3} | 0.73*10^{-3} | 0.83*10^{-3} | 0.21*10^{-3} | 0.73*10^{-3} | 0.82*10^{-3} | 0.73*10^{-3} | 0.10*10^{-3} | 0.83*10^{-3} | 0.73*10^{-3} | 0.83*10^{-3} |

Fig. 23 Energy conversion factors x10^{-3} for all the blocks. The ADC value times the conversion factor gives the energy deposited in the block.
Fig. 22 Total energy in a cluster for 1 GeV incident electrons. The s.d. of the peak gives an energy resolution of $18\%\sqrt{E}$ for the detector.
difference between the extrapolated track and the calculated center of the cluster,

\[ \text{DIFFPOS} = \text{SHOT} - \text{POSCLUSTER}. \] (4.4)

The LG position is adjusted in the analysis till the above mean value is zero. Figure 23 shows the histogram for the above differences in X and Y. The x-axis corresponds to the difference in cm.

The position of the cluster center was taken to be the centroid i.e,

\[ \text{POSCLUSTER} = \frac{\sum \text{EN}_1 \cdot \text{POS}_1}{\sum \text{EN}_1} \] (4.5)

This method biased the data too much towards the block with the maximum energy. This was largely due to the fact that the energy in the blocks in a single cluster is very unevenly distributed. Figure 24 shows the energy in block with the most energy deposited for clusters with one to four blocks. By taking the square root of the energy in the centroid calculation, we can see a dramatic improvement in the position resolution (fig.25). The quantity plotted is the difference between the extrapolated position and the calculated position of the electron (DIFFPOS). The dotted curve shows the data for the regular centroid and the solid curve that for the new centroid (XCL,YCL). The data plotted in fig.25 is a refined sample. It does not contain events which had more than one maxima in the cluster. A small fraction of the data, \( \sim 2\% \), consisted of such events. To include such events the sub-cluster was identified and the energy of the shared
Fig. 23 Difference between calculated and extrapolated electron position.
Fig. 24 Energy deposited in the central block for clusters with 1, 2, 3, and 4 blocks.
Fig. 25a X-Difference between calculated and extrapolated electron position using the normal centroid (dotted) and square root method (solid) for 1, 2, 3, and 4 blocks/cluster.
Fig. 25b Y-Difference between calculated and extrapolated electron position using the normal centroid (dotted) and square root method (solid) for 1, 2, 3, and 4 blocks/cluster.
The block was divided in the ratio of the energies of the two maxima. The data was also subjected to other cuts to remove blocks which cannot be physically part of the cluster. This was done by calculating the distances between the block with the second largest energy and adjacent to the maximum block and all other blocks of the cluster. A block was considered as part of the cluster if the distance was less than 17 cm. The summary of the positron resolutions for X and Y is given in Table 3A and 3B respectively. The data is grouped into three regions: RES-0, RES1 and RES-2. Each set consists of two subsets (1) and (2) which refer to the resolutions obtained by taking the normal centroid and with the square root of the energy respectively. The first set, RES-0, contains events in which there is only one maxima in the block. RES-1 includes events with a local maxima and calculates the position of the cluster by sharing the energy of the common block. RES-2 has an additional cut which rejects events in which the electron does not extrapolate to the block with the maximum energy. RES-3 also contains subset (3) which shows the standard deviation if a gaussian is fitted to the data in subset (2). We see a large improvement in the resolutions for the cases where a gaussian can be fitted to the data.

We looked for corrections by sub-dividing each block into four quadrants each consisting of 16 sub-blocks, and plotting the electron position as a function of the calculated position. The data was summed in such a way that each equivalent sub-block in all four quadrants (+ +), (+ -), (- +) and (- -) were added together. This was done by taking

$$\text{SUB-BLOCKX} = \frac{\text{ABS(XCL - CENT)} \times 2}{\text{DIM(LGMAX)}}$$  

(4.6)
**TABLE 3A**

Comparison of Resolutions X

<table>
<thead>
<tr>
<th>BLOCKS/CLUSTER</th>
<th>RES-0 (1)</th>
<th>RES-0 (2)</th>
<th>RES-1 (1)</th>
<th>RES-1 (2)</th>
<th>RES-2 (1)</th>
<th>RES-2 (2)</th>
<th>RES-2 (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.65</td>
<td>1.65</td>
<td>1.65</td>
<td>1.65</td>
<td>1.64</td>
<td>1.64</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>1.86</td>
<td>1.53</td>
<td>1.87</td>
<td>1.59</td>
<td>1.81</td>
<td>1.55</td>
<td>1.46</td>
</tr>
<tr>
<td>3</td>
<td>1.86</td>
<td>1.54</td>
<td>1.87</td>
<td>1.60</td>
<td>1.80</td>
<td>1.55</td>
<td>1.22</td>
</tr>
<tr>
<td>4</td>
<td>1.96</td>
<td>1.87</td>
<td>1.98</td>
<td>1.91</td>
<td>1.91</td>
<td>1.84</td>
<td>1.77</td>
</tr>
<tr>
<td>5</td>
<td>2.13</td>
<td>2.24</td>
<td>2.15</td>
<td>2.25</td>
<td>2.04</td>
<td>2.16</td>
<td>---</td>
</tr>
</tbody>
</table>

**TABLE 3B**

Comparison of Resolutions Y

<table>
<thead>
<tr>
<th>BLOCKS/CLUSTER</th>
<th>RES-0 (1)</th>
<th>RES-0 (2)</th>
<th>RES-1 (1)</th>
<th>RES-1 (2)</th>
<th>RES-2 (1)</th>
<th>RES-2 (2)</th>
<th>RES-2 (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.64</td>
<td>1.64</td>
<td>1.64</td>
<td>1.64</td>
<td>1.63</td>
<td>1.63</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>1.82</td>
<td>1.63</td>
<td>1.83</td>
<td>1.67</td>
<td>1.79</td>
<td>1.64</td>
<td>---</td>
</tr>
<tr>
<td>3</td>
<td>1.94</td>
<td>1.61</td>
<td>1.95</td>
<td>1.66</td>
<td>1.88</td>
<td>1.61</td>
<td>1.57</td>
</tr>
<tr>
<td>4</td>
<td>2.01</td>
<td>1.79</td>
<td>2.02</td>
<td>1.84</td>
<td>1.93</td>
<td>1.75</td>
<td>1.38</td>
</tr>
<tr>
<td>5</td>
<td>2.16</td>
<td>2.09</td>
<td>2.18</td>
<td>2.10</td>
<td>2.10</td>
<td>2.03</td>
<td>---</td>
</tr>
</tbody>
</table>
where SUB-BLOCKX corresponds to the fractional distance from the center of the block in both x directions. SUB-BLOCKY was calculated in a similar manner. DIM(LGMAX) is the size of the block with the largest fraction of the cluster energy. Block (2,3) then corresponds to SUB-BLOCKX and SUB-BLOCKY being between 0.25-0.50 and 0.50-0.75 respectively. The data was plotted for two, three and four blocks in the cluster. For clusters with more blocks, there is not much statistics. Clusters with a single block have the intrinsic resolution of the detector and no corrections can be made. We can only calculate the spread of the electron tracks from the center of the block and smear the calculated positions over this region in a random fashion. Figure 26 shows the track distribution for clusters with one block. We see that if the electron falls inside a circle with a radius of ~2 cm all the energy is contained in that single block. This is also borne out by the data shown in Fig.25 where the standard deviation for a cluster with one block is 1.65 cm which is the correct number for the smaller SF2 blocks. A similar situation occurs for clusters with two blocks lying in the same row. The y-position is always calculated as the center of the block reducing the position resolution in Y. The staggered nature of the rows does not let this happen for the x-position.

Plotting the electron track distribution as a function of the calculated cluster centroid we see that in most of the cases, the histograms are flat over half of the quadrant. There is no correction possible for such cases (fig.27). Using the data for each sub-block in each cluster, we looked for shifts in the peaks. We see in figure
Fig. 26 Electron track distribution from the center for clusters with 1 block.
Fig. 27 Electron track distribution for clusters with 2 blocks when the calculated electron position lies in sub-block X(2,3).
Fig. 28a X-Difference between calculated and extrapolated electron position using the square root method with and without (solid, dotted) corrections for 1, 2, 3, and 4 blocks/cluster.
Fig. 28b Y-Difference between calculated and extrapolated electron position using the square root method with and without (solid, dotted) corrections for 1, 2, 3, and 4 blocks/cluster.
28 the corrected histograms for the different clusters. The solid histogram is from the corrected data and the uncorrected data is plotted as a dashed histogram. There doesn't seem to be much difference between the two plots. This is because only a few of the sub-blocks had corrections, many had very low statistics for a clean correction, and depending on the configuration of the cluster the data showed double peaks, which does not lend itself to corrections (Fig.29) This is a disadvantage of using different size blocks.

4.5. pion

The decay of $\pi^0$ into two photons is particularly useful to test the lead glass. The mass reconstruction of the $\pi^0$ will utilize the basic techniques for detecting the photon from $\Sigma^0$ decay. The trigger required the photon showers to be in separate halves of the array, upper and lower five rows. After extracting the energies of both photons, $E_1$ and $E_2$, using the fit parameters from ABCALC, the mass is calculated using the formula

$$m = \sqrt{(2*E_1*E_2*(1 - \theta))} \ldots \ldots \ldots \ldots \ldots \ldots (4.7)$$

where

$$\theta = p_1 \cdot p_2, \text{ and } E_1 = \sqrt{p_1^2}.$$

The energy resolution is spoilt because the longitudinal containment of the shower is incomplete. The position resolution errors manifest themselves in the mass of the $\pi^0$ through the determination of the momentum of the photons.

There were 60,000 events with and 9,600 events without the MPS magnet on. Figs 30a,b show the two reconstructed peaks for the data with and without the MPS magnet respectively. The mass was also
Fig. 29 Double peaked structure in electron track distribution for cluster position calculated in sub-block Y(2,2).
Fig. 30a $\pi^0$ mass spectrum with MPS magnet on. Solid: cluster position calculated using normal centroid method; dotted: square root method.
Fig. 30b Π^0 mass spectrum without MPS magnet on. solid: cluster position calculated using normal centroid method; dotted: square root method.
calculated using the square root method to find the cluster position (dotted curve).

We obtain

\[ m_{\eta_0} = 135.25 \pm 12.92 \text{ MeV} \]

and,

\[ m_{\eta_0} = 133.64 \pm 13.20 \text{ MeV} \]

with and without the MPS magnet respectively. The widths are smaller by approximately 0.4 MeV for the case where the position is calculated using the square root of energy. The means stay about the same.
CHAPTER 5

CONCLUSIONS

We have measured the energy and position resolution of a lead glass electromagnetic calorimeter. The detector's response is directly proportional to the energy of the incident particle up to 3 GeV. The proportionality constants have been determined for each block. The energy resolution has been determined to be $18\%\sqrt{E}$ by looking at the energy of the reconstructed cluster. This is verified by reconstructing the mass of the $\pi^0$ by measuring the two photon showers from its decay. The position resolution is more complicated because of the different sizes and asymmetric positioning of the blocks. We obtain a resolution of $\approx 2$ cm for a 1 GeV incident electron.

The detector was subsequently used in E817 in Dec 87-Jan 88. It was observed that the LEDs had all changed since the time of the calibration which was six months ago. The increase is on an average 10%. A few blocks drifted in the other direction. The LEDs for the experimental run are shown in Fig. 31 as absolute values (a), and as a deviation from the final LED data set values from the calibration. Taking into account the change in the LED values at the same high voltages the energy conversion factors were adjusted for the photon shower. The $\Sigma^0$ mass so obtained is shown in Fig. 32. The mass peaked
b.) % Variation wrt LED Data Set 3

a.) LEDs During The Experiment

Fig.31
Fig. 32 $\Sigma^0$ mass peak from the experiment.
at ~1210 MeV before corrections. The mean of the fit is 1198 ± 14 MeV. The accepted mass of the Λ⁰ is 1192.46.
LIST OF REFERENCES.

1. C. Fabjan; Techniques And Concepts In High Energy Physics, T. Ferbel ed.


   F. Abe et al; Phys. Rev. Lett. 50, 1102 (1983)


6. S.Y. Hsueh et al; Fermilab Pub 85/21-E